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THE POLARIZING PHOTO-CHRONOGRAPH.

BEING AN ACCOUNT OF EXPERIMENTS AT THE U. S. ARTILLERY SCHOOL, FORT MONROE, VA., IN DEVELOPING THIS INSTRUMENT.

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This Book is Dedicated

TO

THE BOARD OF ORDNANCE AND FORTIFICATION,

UNITED STATES ARMY.

PREFACE.

The idea that these papers, which originally appeared in the *Journal of the United States Artillery*, should be republished in book form was not thought of until the last paper describing the new instrument recently installed at the Artillery School was about to be published. The reprints of the first paper, which contains a discussion of the general principles upon which the operation of the chronograph depends, soon became exhausted, so that it was desirable to have it republished in some form. At the suggestion of friends and through the courtesy of the Editor of the *Journal* it was arranged to publish the collected papers in the form now submitted.

In deciding upon a plan of presentation it was thought that the original papers without change, as representing historically the particular point of view in mind at the time they were written, would give to others in the best manner the account of the development of the new instrument thus far, which is the object of this publication. The first paper, describing the principles involved and the rough apparatus used in the early experiments, was originally written in part to present the matter to the Board of Ordnance and Fortification for the purpose of securing financial aid to build an accurate instrument based upon these principles. Being successful in interesting the Board in the development of the instrument, the next step was naturally to make some further experiments both in the improvement of the instrument and in testing its usefulness as applied to the measurement of interior velocities. The account of these experiments forms

the subject of the second paper, originally presented as a report to the Board of Ordnance and Fortification. This also served as a preparation for the design and construction of the final form of instrument, which was next to follow. The instrument was finished and installed at the United States Artillery School, Fort Monroe, Va., during the summer of 1896.

An opportunity was presented at that time of making some further experiments with the new instrument used as a means of recording variable or alternating currents, especially in the interesting cases of "make" and "break." The third paper, submitted as a report to the Board, contains a detailed description of the new Instrument, with its accompanying Measuring Instrument, for the purpose of measuring the angles upon the negatives obtained, together with some account of the experiments upon alternating currents which illustrates its elastic character. As yet no trials with guns of larger caliber than the 3".2 field gun have been made through lack of time and opportunity. It is thought that the results obtained with the smaller gun justify a careful set of experiments with larger guns, though it is true that these require a much larger equipment of machinery in the shops, and would occupy a longer time.

The original paper by Dr. Crehore, upon *A Reliable Method of Recording Variable Current Curves*, published in the Transactions of the American Institute of Electrical Engineers for October, 1894, is added by way of appendix, because it gives a more complete treatment of Faraday's discovery of the phenomenon of the rotation of the plane of polarization of light by a magnetic field, for reference by any who may wish to examine the subject more in detail from a purely physical standpoint.

To Lieut. B. W. Dunn, Ordnance Department, U. S. A., we are indebted for the method by which he has increased the possible accuracy of tuning-fork records for the measurement of minute intervals of time.

It is a pleasure to acknowledge the large number of letters received from scientific and military experts of many parts of

Europe as well as this country, containing suggestions and applications which have been a constant source of encouragement and inspiration to further work.

We feel it but a poor recognition to record our obligations to Colonel Royal T. Frank, 1st Artillery, Commandant of the Artillery School, for placing the resources of the laboratories of the School at our disposal for conducting these experiments, and especially for his support during the early experiments, before official recognition and financial aid had been received to carry on the work.

A. C. C.
G. O. S.

U. S. Artillery School, Fort Monroe, Va.,
March, 1897.

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INTRODUCTION.

The word chronograph means an instrument which is literally a time writer, that is, one which is capable of measuring and recording the times of certain events. From the conditions which in the nature of things are always required of it, the word chronograph has an additional meaning. The events to be recorded seldom happen at the place where the instrument is located, and thus arises the necessity of communicating immediately upon its occurrence the event to the chronograph proper.

The means of communication used, since it is a comparatively simple matter to record events happening at the instrument, have in fact become the all-important part of a chronograph, so much so that the merits and demerits of a given instrument are usually decided by considering it alone.

Before entering upon the design of an instrument based upon the principles to be described, the construction of the best modern chronographs was studied and analyzed from the foregoing point of view. In a large class of these instruments, all of which communicate the intelligence from the place where the event happens to the chronograph by means of the electric current, the record is eventually made by a stylus or indicator connected to the armature of an electromagnet. The armature evidently is set in motion after the event to be recorded has happened. The delay is due to a number of conspiring causes, one of which is the inertia of the armature itself; another, the time required to magnetize the iron; another, the electrical properties of the line conveying the information.

Another class of instruments use no moving armatures, but employ an electric spark, obtained from a circuit wound around an iron core, and usually from a circuit independent of the line, such as the secondary of an induction coil. The spark pierces a prepared surface, and leaves its record upon it. This is found to be a source of slight error, as the successive sparks do not proceed from the same point by identically the same path. There is also the delay due to the presence of the iron, the magnetic behavior of which is known to be dependent upon its past history, and also some delay from the use of a secondary coil.

It is understood that the intervals referred to above are exceedingly small quantities, and quantities which may possibly be made of equal duration in successive records, so that the differences in time will correspond accurately to the actual events. Notwithstanding this possibility, it is certainly more satisfactory to use an instrument where one is sure that these intervals are negligible, and it is this thought which naturally leads to a consideration of the possible agents which are available for such a purpose. Such agents are to be found in Light and Electricity, when it is remembered that the velocity with which either of these agents travels is the enormous speed of 186,000 miles per second, that is, more than seven times around the earth in a single second of time. The use of light alone, if rightly applied, is sufficient to answer all the purposes of a chronograph transmitter; but this plan would lack the essential feature of convenience in practical manipulation for most purposes, which renders it prohibitive. The combination of the two agents Light and Electricity meets the requirements from the practical standpoint, and makes possible a theoretically quick and convenient arrangement. The employment of the two agents together, however, would not admit the use of a connecting link between them which is inferior in point of speed to either of them, so that one is forced to ask what are the known points at which Light and Electricity meet? Where does a beam of light ever have any direct influence upon electricity in any of its

manifestations? Or where does electricity directly influence a beam of light? This was the question which Michael Faraday carried prominently before him in the early part of the nineteenth century, when there was no then known connection between these two great agents. It was to his remarkable perseverance in experimenting, due probably to the keen insight and native intuition he possessed, which finally led him to discover the first direct connection between Light and Electricity in a surprisingly remote and unsuspected place. He did not find this effect until a particular kind of light was used, in which the vibration is confined to one plane, known as the plane of polarization of the polarized light, and then the effect could not be noticed until the light was analyzed. By passing the polarized beam through certain substances situated in a strong magnetic field, and in such a direction as to coincide with the lines of magnetic force, it was found that the plane of polarization was rotated as detected by the analyzer, when it was not rotated without the magnetic field. Different substances possess this property in different degrees, but the amount is very small as compared with those substances which possess this property naturally, without the aid of the magnetic field. It is the application of this discovery, viz., the influence of the magnetic field as generated by the electric current upon light, which is the basis of the chronograph to be described in the following papers.

Since this first discovery by Faraday others have been found which reveal the intimate relations existing between Light and Electricity, one of these being that they each travel through space with the same velocity.

The use of Light as the agent in a chronograph is greatly facilitated by the recent development of rapid photographic plates, which only require the shortest exposures to intense light. Exposures as short as the 1/10,000 or even the 1/100,000 of a second are found practically sufficient to make permanent records on the sensitive plates with even moderate light intensity, as compared with that intensity which may be obtained.

Since Faraday's discovery many substances have been examined with reference to their specific rotatory power, though it seems that the list of available materials has by no means been exhausted. The desirable qualities for such a substance in the present application are high transparency combined with great specific rotatory power. It must also be especially transparent to the shorter wave-lengths, or blue rays of light, to be particularly efficient with a photographic plate. Carbon bisulphide possesses these qualities to a considerable degree, and, moreover, is very easily obtained; but it is probably not the most desirable substance to employ.

An examination of the list of substances which have been tested fails to reveal any regularity, either in physical properties or in chemical constitution, which might serve as a guide to the experimenter in searching for substances of great specific rotatory power. If a substance could be found which possesses much greater rotatory power, so that it might be operated by a smaller amount of power, there is no doubt that the usefulness of the instrument for some purposes would be increased.

The researches of Verdet have given us definite data as to the fall of magnetic potential required to produce a given rotation of the plane of polarization, and this value is large when compared with a substance like quartz, which naturally possesses the power of rotating the plane without the magnetic field. It requires, for instance, approximately 35,700 ampere-turns wound upon a tube containing carbon bisulphide to produce the equivalent rotation of a quartz plate one millimeter in thickness.

Roughly speaking, the coils for the carbon bisulphide tubes, described in the following papers, require considerable electrical power to operate, but it must not be inferred that this is necessarily the case to produce satisfactory records upon the photographic plate. The great perfection which has been reached in rapid photographic plates already referred to, as well as the fact that the light from a powerful electric arc is concentrated

through the tube to be operated upon, makes the matter of possible sensitiveness of the receiver only determined by thorough tests.

Although the time has not been afforded as yet for entering into the question of the most desirable size and shape of receiver tubes and the minimum amount of power necessary to produce good records upon the plate, yet a few trials have been made with this in view, and it is hoped they may be continued. Perfectly clear and strong records have been easily obtained through a tube 40 cms. long and of 1.5 cms. inside diameter, with an expenditure of about sixty watts power, or about that consumed in an ordinary 16 candle power incandescent lamp.

EXPERIMENTS WITH A NEW POLARIZING PHOTO-CHRONOGRAPH, APPLIED TO THE MEASUREMENT OF THE VELOCITY OF PROJECTILES.

THE experiments forming the subject of this paper were conducted between the dates of the 27th of December, 1894, and the 12th of January, 1895, at the United States Artillery School, Fort Monroe, Virginia. This time was chosen because it came during the holiday vacation, and was the only time that either of us could devote uninterruptedly to the work. The object in making these experiments was to test a new instrument as applied to the measurement of the velocity of projectiles. In May, 1894, a paper* in which was described a new method for measuring any kind of a variable electric current, no matter how sudden or abrupt the change in the current, was read at the general meeting of the American Institute of Electrical Engineers in Philadelphia. A point of superiority of this instrument over other known methods of measuring currents is the fact that, in recording a variable current, no *ponderable matter* is required to be moved, as is the case with other instruments for this purpose. Many examples of other instruments might be mentioned, but in each case a certain amount of ponderable matter possessing inertia is required

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* "A Reliable Method of Recording Variable Current Curves," by Dr. A. C. Crehore.

Transactions of the American Institute of Electrical Engineers, October, 1894.

The Physical Review, No. 2, Vol. II, 1894. See Appendix.

to be moved, as, for instance, when a telephone is used upon the disk of which is mounted a mirror that permits a beam of light to be reflected from it: any vibration of the disk gives an angular motion to the beam of light, and this motion is in turn recorded upon a moving photographic plate. In this instance the matter which is required to be moved is the disk and the mirror mounted upon it. When the current varies it is compelled to do work in moving the disk on account of the inertia of the moving part. As a consequence of this, the motion of the beam of light lags behind the position it should occupy to represent the current accurately.

The relation between an instrument which will accurately measure a variable electric current and the measurement of the velocity of projectiles may not be evident at a glance. In regard to this, it may be said that any good instrument for measuring a variable current possesses the essentials of a chronograph, and a chronograph is the essential instrument for measuring the velocity of projectiles. A good current [illegible] must give sufficient data to construct a curve, the horizontal axis representing time and the vertical axis the current. The time intervals between any phenomena can therefore be measured by such an instrument, if the phenomena referred to are capable of either interrupting the electric current or [illegible] in any way.

Upon the publication of the article referred to, it occurred [illegible] who was at the time considering means for [illegible] the known methods of measuring the velocity of [illegible] that the instrument would be well adapted for the [illegible] a correspondence between us, by which it [illegible] undertake these experiments at the earliest [illegible], and accordingly authority was obtained from [illegible] Commandant of the Artillery School, [illegible] ammunition and the use of the resources of the [illegible] of the school for the prosecution of the work, and [illegible] support and encouragement throughout that

these experiments were made possible. Preparations for the experiments were immediately begun. A temporary proving ground was fitted up about seventy-five yards from the laboratories of the Artillery School, and the necessary ballistic lines and screens installed for operating two Boulengé instruments. At Dartmouth College, where the original apparatus was prepared, a special camera was made, which is described later, and the whole instrument was shipped to Fort Monroe on December 19.

For the purposes of a chronograph the original instrument is simplified by omitting the part of the apparatus producing the spectrum, and by recording instead the persistence and interruptions of the white light emerging from the analyzer. The nature of the instrument is such that it is admirably adapted for recording the passage of the projectile at a number of points of its trajectory, which points of observation may be as near together as is desirable. For this reason it was made an object to study the *law of variation* of the velocity of the projectile near the muzzle of the gun. Observations were generally taken within a distance of forty-five feet from the muzzle at various regular intervals. As many as ten observations at regular intervals of only five feet, beginning at the muzzle of the gun and extending to a distance of forty-five feet, were obtained. From measurements on the negatives, it is clearly evident from each that the velocity of the projectile actually increases after leaving the gun. This is a fact which has long been suspected, but which, so far as we know, has not been previously demonstrated experimentally.

Principles Utilized in the Chronograph.

The method of measuring the velocity of projectiles described in this paper is the same in one essential particular as the methods now practiced. The projectile passes through screens, and the velocity is obtained from the two independent measurements of

the distance between the screens and the time interval. The instrument is not a "one-point velocimeter," by which the velocity may be measured by a single observation of the projectile at one point of its trajectory, which is a conceivable thing; but is a new form of chronograph to measure the time interval between the screens. The spaces are measured independently. As a chronograph, the instrument has a wide application to many phenomena of nature, besides the single application to the measment of the velocity of projectiles.

The Chronograph.

The desirable and possibly essential features of a good chronograph may be classed as follows: First, there must be some agent which can transmit from the phenomenon to be recorded wherever it may be located, the occurrence of the event to a place where it can be permanently made a matter of record. Second, the agent which is to receive the record must include with it some accurate means of measuring time. For brevity, let us designate these two parts of any chronograph by the terms "transmitter" and "receiver." The transmitter will then include all those parts of any chronograph which are instrumental in conveying the occurrence of the event from the place where it happens to the agent which finally receives the record. The receiver includes all those parts that are essential in receiving the record, together with an accurate means of measuring time.

(*a*) *The Transmitter.*

It would be said that a transmitter were a good one if the time interval that elapses between the occurrence of the phenomenon to be recorded, and the actual recording of it upon the receiver were absolutely zero. It need not be said that all we may hope to do in practice is to approach that condition as nearly as possible. However, where we are only concerned with

differences in time, we have the fortunate condition that any error disappears in taking the difference, if the times of transmission are always exactly alike. The chance of error is also greatly reduced if these intervals of transmission are made as small as possible.

The particular form of transmitter used in these experiments depends for its action upon the use of polarized light. Though the principles of polarized light are familiar to many, such an essential part of the chronograph depends upon them, that it is hoped the following explanation is not entirely uncalled-for.

Let us admit a beam of sunlight through a small aperture into a dark room, and let it fall upon a sensitized photographic plate. If the plate is moved transversely across the beam, it will be found that the negative shows a continuous band of light. Now suppose that the aperture which admits the beam of light is provided with a shutter that can be opened or closed at will. As the sensitive plate moves across the beam, let the shutter be successively opened and closed. The negative now shows an interrupted band of light, alternately light and dark, due to the opening and closing of the shutter. If the beam were admitted to the plate through a narrow slit, it would be possible to make the band of light stop off suddenly at a definite point on the negative. If it is known just how fast this sensitive plate moves across the beam, it would be easy by measuring the distance between two points on the plate to measure the time intervals between the opening and closing of the shutter. Again, the shutter might be operated by some agent whose time interval we desire to know, and thus a measure of it obtained. If the shutter could be manipulated quickly enough by a projectile, we might thus measure its velocity; but if we attempt to make any *material* shutter, that necessarily possesses a certain amount of *inertia*, move back and forth at the instant the projectile passes a screen, we must surely fail. The experiment is more successful, however, when we use a shutter that has absolutely *no mass.* This is the kind of shutter which was used in these

experiments, and it was with this object in view to obtain a massless shutter, that we have made use of polarized light.

In the path of the beam of white light admitted through the aperture is placed a Nicol prism (any other means of obtaining polarized light may be employed) in order to obtain a beam of plane polarized light. This prism is made of two crystals of Iceland spar, which are cemented together by Canada balsam in such a way as to obtain only a single beam of polarized light. The crystal is a doubly refracting medium, that is, a light beam entering it is in general divided into two separate beams which are polarized and have different directions. One of these beams in the Nicol prism is disposed of by total reflection from the surface of separation where the Canada balsam is located, and the other emerges a completely polarized beam ready for use. What happens may be thought of as follows: White light is made up of transverse vibrations in the ether having all sorts of directions. By the word *transverse* is meant that all these vibrations are confined to planes which are perpendicular to the direction of the beam of light, and in white light the vibration is any sort of an irregular curve in these planes. In the doubly refracting crystal, when this beam is divided up into two, taking different directions, it is found that each beam has only one component of the vibration of the original light. One beam has all the up and down components, while the other has all the right and left components. Each of these beams is called plane polarized, because each has vibrations in a single direction only, perpendicular to the direction of the ray. As the wave advances, all the motion will thus be confined to a single plane containing the ray. This is the plane of polarization. We may say that the function of the Nicol prism is to sort out from a beam of light all those vibrations which are not parallel to a certain plane in the prism.

Suppose that a second Nicol prism exactly like the first is now placed in the path of the polarized beam. It also has the power of sorting out all vibrations not parallel to a certain plane

in itself. If then the second prism called the "analyzer" is set so that its plane is just perpendicular to that of the first prism called the "polarizer," all the vibrations not sorted out by the polarizer will be by the analyzer. In this position, the planes being just perpendicular to each other, the prisms are said to be "crossed," and an observer looking through the analyzer finds the light totally extinguished as though a shutter interrupted the beam. By turning the analyzer ever so little from the crossed position, light passes through it, and its intensity increases until the planes of the prisms are parallel, when it again diminishes; and if one of the prisms is rotated, there will be darkness twice every revolution.

In order to accomplish the same end that is obtained by rotating the analyzer without actually doing so, the following means is adopted: Between the polarizer and analyzer is placed a transparent medium which can rotate the plane of polarization of the light subject to the control of an electric current without moving any *material thing.* The medium used in these experiments was liquid carbon bisulphide contained in a glass tube with plane glass ends. There are many other substances which will answer the purpose, some better than others. This was selected because it is very clear and colorless, and possesses the necessary rotatory property to a considerable extent. It only possesses this property, however, when situated in a magnetic field of force. The rotatory power is proportional to the intensity of this magnetic field.

To produce a magnetic field in the carbon bisulphide, a coil of wire is wound around the glass tube and an electric current passed through the coil. When the current ceases the carbon bisulphide instantly loses its rotatory power. The operation is as follows: First, the polarizer and analyzer are permanently set in the crossed position, so that no light emerges from the analyzer. A current is now sent through the coil on the tube. The plane of polarization is immediately rotated. This is equivalent to rotating the polarizer through a certain angle, and hence light

now emerges from the analyzer. Break the current, the medium loses its rotatory power, and there is again complete darkness. This arrangement makes an effectual shutter for the beam without moving any mass of matter.

The whole time of transmitting the phenomenon to the receiver may be thought of as consisting of three distinct operations, which occupy three successive intervals, as follows:

1. The interval due to change in the current;
2. The lag of the magnetic field in the solenoid behind the current which caused it;
3. The time occupied by the rotation of the plane of polarization, and the transmission of the light from the transmitter to the receiver.

If we consider these intervals in the inverse order to that in which they are enumerated, the time taken by the light in travelling from the tube to the receiver, a distance of perhaps a meter, is only 3.33×10^{-9}, or .000,000,003,33 seconds, a quantity a thousand times smaller than that measured with the instrument. The other part of this interval, that of rotating the plane of polarization, we cannot speak of with the certainty of an experimental determination, for we know of no experiments that have ever been carried out bearing directly on this point, that is, to ascertain whether the rotation of the plane of polarization takes place in unison with a change in the strength of the magnetic field, or whether it lags behind it, and if so how much. If such a determination were experimentally possible, it would seem that its answer would throw much light upon the connection between the ether and ordinary matter. It may be considered as practically certain, however, that this lag, if any such exists, is of the order of magnitude mentioned above, and cannot affect any measurable quantity. In taking differences this interval will vanish, as the times must be alike in any two instances.

The second interval, the lag of the magnetic field behind the electric current, depends in part upon whether there is in the magnetic field any magnetic material. If there is iron

present, this interval might have a decidedly important value, since it might not only have an appreciable magnitude, but most of all it might vary from time to time, depending entirely upon the past history of the iron, as has been repeatedly and conclusively shown by experiment. But the case is different where no iron or magnetic material is used, for then the magnetic field is propagated into the space surrounding the solenoid in waves that travel onward with the velocity of light, so that within a few centimetres only of the solenoid the field is in perfect unison with the current. For these reasons there was no iron used in the space near the solenoid in these experiments.

The intervals involved in the last two operations may be neglected in comparison with the first mentioned. The current always does take some time to decrease from its original value to zero, and the light is not put out until the current is zero, though it gradually goes out as the current diminishes. There is no fixed law of decrease of current in a circuit containing resistance and self-induction when the current is broken, i.e., when the resistance is increased from its original value to infinity, or the conductivity is reduced to zero; for the current must depend upon the law of variation of this resistance. The resistance might be gradually increased, so that a comparatively long time is occupied by the current in coming to zero. The case of a "break" is apt to be sometimes confounded with one which is entirely different in its nature. When an electromotive force is suddenly removed from a circuit, *the resistance remaining the same*, the current dies away according to a curve known as the exponential curve, and by this law the current reduces to $\frac{1}{\epsilon}$th of its value after a time T that depends only upon the resistance and inductance of the circuit. This T is known as the time constant of the circuit, and is equal to L/R, the inductance divided by the resistance. This law has no application, of course, in the present instance, and cannot be used; for here we actually let the constant electromotive force remain in the circuit, and, far from allowing the resistance to remain

the same, we increase it to infinity. The process may perhaps be thought of as follows with advantage: When the circuit breaks, the resistance offered to the passage of the current becomes very great indeed in the gap formed. If the current is to obey Ohm's law it must quickly decrease to a much smaller value. The very act of decreasing the current sets up an electromotive force, called the counter electromotive force of self-induction, in the same direction as the current. The magnitude of this electromotive force depends upon the rate of change of the current, and also upon the inductance, and it may therefore become very large. The induced electromotive force is in fact equal to $e = - Ldi/dt$. This electromotive force attains so high a value that the current passes right over the gap between the conductors and establishes an arc between the two severed metals, which accounts for the spark that is always observed when a circuit is broken. This arc lasts as long as the electromotive force is great enough to keep it up. It may be that the constant electromotive force acting in the circuit is large enough to maintain this arc, and we have an arc continually established, as between the carbons in an arc-lamp. The moment the terminals are so far removed that neither the induced nor the constant electromotive force, nor their sum, can bridge the gap, then the current stops. Though we cannot hope to know the exact time which this arc occupies by any mere speculation, it has been experimentally determined in certain instances, and where certain metals are used as electrodes; and in general it should be so determined in each particular instance.

The foregoing considerations are useful, however, as a guide for the experimenter, to show him certain channels which it will be well for him to follow to attain the best results. We may be certain of one thing by referring to the expression for the induced electromotive force: We diminish the induced electromotive force just in proportion as we diminish the inductance of the circuit, for it enters as a direct factor there. This indication was followed in the experiments, and the self-induction of the

coil upon the tube of carbon bisulphide was made in four sections, so that they might all be joined in parallel, and thus reduce the self-induction of the tube sixteenfold as compared with what it would have been had all the coils been connected in series. The more exact description of the apparatus is deferred until later.

Another point which may be noted is that the projectile mechanically breaks the circuit as quickly as it is possible to be done by any agency. But the exact influence of this is not so easy to predict, for though it is probable that the current dies away quicker with a sudden break than it does with a very slow one which permits the arc to remain for some time, yet it is not proved certainly, for the more rapidly the break is made, the faster the resistance increases and therefore probably the rate of change of current, and with it the counter electromotive force increases. An increased electromotive force can bridge a longer gap, but a longer gap may be made in the same time that a short one is with a less velocity at the break. So it appears that these two considerations counteract each other, and all depends upon which has the greater influence. The former consideration, however, seems to favor the view that the quicker the break, the sooner the current will cease.

The most important consideration of all in respect to this time interval, which is at the same time most fortunate, is that for taking differences of time these intervals are the same in all cases. For exactly the same circuit is used, and the inductance is necessarily the same; also, the break is made at the same rate (or approximately so) in all cases. This relieves us of any necessity of making two electromagnets exactly alike (as is required in the Boulengé Chronograph); and even if the magnets are exactly alike as to shape, it has been shown that two pieces of iron from a common original bar depend for their action upon their past magnetic history, which may, of course, be entirely different in the two cases. There is no objection to this chronograph on the score that there are masses of matter to be moved

or that there are iron-cored magnets used in its operation, for there are none. This will hardly be claimed for any other chronograph with which we are familiar.

(*b*) *The Receiver.*

The receiver is that part of the chronograph which is susceptible of receiving the continuous record from the transmitter, and it also includes that part of the instrument which measures time. A receiver is a good one when the exact law of relative motion between it and the recording part of the transmitter is known, so that every point of the record of the receiver represents a certain definite known time. Different instruments may have different laws of motion: for instance, one may be a falling body whose motion is uniformly accelerated, another may be uniform motion of translation, or, again, we may have a uniformly rotating receiver. There are various means of approximately obtaining these different motions; but let it suffice to describe the receiver used in these experiments. It consisted of a circular photographic plate upon a horizontal shaft in a dark box. An approximately uniform rotation was given to it by means of an electric motor, whose armature was coupled directly to the shaft. In order to determine the angular velocity of the plate accurately, whenever it is exposed, a tuning-fork is placed so that the shadow of one prong is projected sharply upon it by means of a parallel beam of light from an intense source. The light from the transmitter, as well as the light from the tuning-fork, is admitted to the plate through a narrow horizontal slit. When the plate is in rotation, and the tuning-fork is vibrating, the shadow of the edge of the fork describes a sinusoidal line around the plate. From a knowledge of the angle on the plate, which a certain number of these waves subtend, and the time of vibration of the fork, the angular velocity of the plate at once becomes known. The real time measurer is thus a tuning-fork, which is a most reliable method of measuring time. Moreover,

the speed in each instance is recorded upon the plate at the instant the chronograph record is made, so that the necessity of measuring the speed before and after the observation is avoided.

It need not be said that the various parts of both the transmitter and receiver might be constructed in other and better ways, and the manner of their use and operation modified in many particulars which it would be out of place to describe here.

Description of Apparatus.

The gun used was a 3.2-inch B. L. field rifle, No. 56, model of 1892, and the service charge of $3\frac{3}{4}$ lbs. of I. K. H. powder was uniformly employed. The projectiles were common shell, so selected that each weighed 13 lbs. 6 oz.

Length of bore of gun	25.2 calibres.
Travel of projectile in bore	21.81 "
Powder-chamber capacity	108.9 cu. ins.
Density of loading	0.95315.

For the gun two siege-platforms were laid in prolongation and levelled, giving a suitable direction of fire out to sea. The firing was conducted without applying the wheel-brakes, and the recoil was approximately constant at 48 feet total, or 28 feet on the platform and 20 feet on the ground.

The arrangement of screens for this work possesses some interesting features. A skid *AA* (Fig. 1) 12″ × 12″ and 15′ long, was placed in approximate prolongation of the axis of the bore with the gun elevated at 3°, being supported by two solid upright posts *BB*. Beyond this shifting planks were placed end to end, spiked together and supported by 2″ × 4″ scantlings set into the ground at intervals, as shown in the figure. Two large ballistic screens, shown at *C* and *D*, were erected, at distances respectively of 44 feet and 118.2 feet from the muzzle, for the use of the Boulengé chronograph (Bréger modification) for purposes of comparison.

A screen for these experiments which is but a foot wide is shown at *E*, and is made by two strong upright pieces spiked to the sides of the skid. Along the straight edge of these pieces, on the side towards the gun, wire nails were driven in at close intervals, and insulated wire wound around the nails and stretched back and forth, three times across being usually sufficient on account of the accuracy of the gun. The ends of each screen wire were attached to the line wires which were run along on either side of the trajectory, the insulators being shown at *FFF*. This method of making the screens near the muzzle a part of a heavy beam, placed end-on in prolongation of the axis of the gun, permitted greater accuracy in measuring the distances between screens by a steel tape stretched taut along the beam; and the whole arrangement, also, presented a minimum surface to the blast, the effect of which at first was much overestimated. The smallness of the screens, and the uniformity in the make-up of each, tended to reduce any error caused by the projectile not cutting the wires of each in exactly the same manner. During the progress of the experiments the screens were placed at various intervals, the final arrangement being five-foot intervals up to 45 feet from the muzzle. The first screen was uniformly

A is the wooden body of the device, *BB′* binding-posts for connecting in the line wire, *CC* the brass springs. The tapering jaws of the springs press firmly together, forming an electrical connection between the binding-posts *BB′*. When, however, a minute insulating plug *D* is inserted between the jaws, *B* and *B′* become insulated from each other. A wire is attached to the insulating plug and stretched across the path of the projectile, to be mechanically pulled out by the projectile during its passage, thus re-establishing the current in the line wire, and consequently

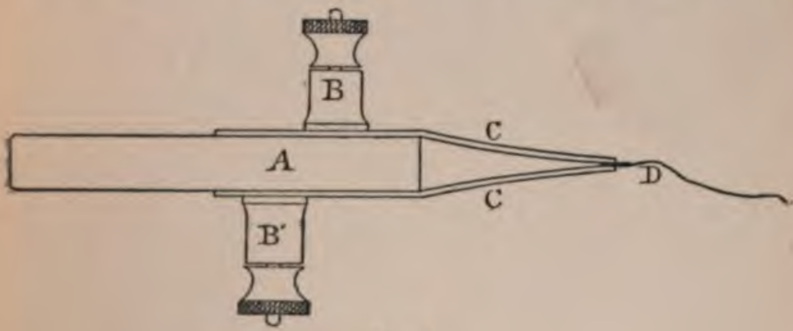
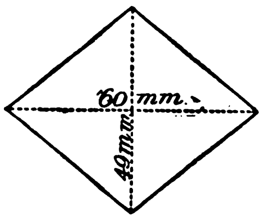


FIG. 2.

through the next screen. Various insulating materials were tried in the search for one which would possess the requisite toughness to withstand the powerful shock caused by the projectile hitting the wire, and at the same time permit of being bevelled to the minute thinness at its edge which was required for such quick action. Hard rubber, rawhide, and rubber belting were tried, but hard sole-leather was found to work best.

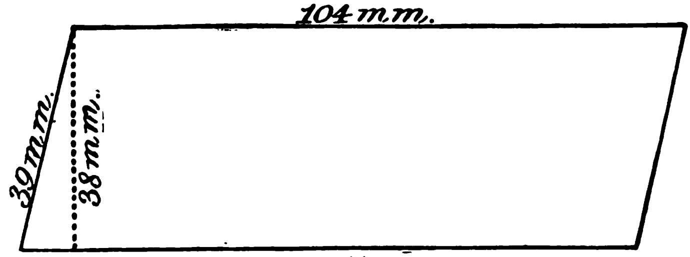
In addition to the necessary wires to the ballistic room for operating two Boulengé instruments, four line wires were run from the gun-platform to the electrical laboratory, two for the primer circuit for firing the gun, and the other two for the chronograph transmitter.

THE TRANSMITTER.



End.

In Fig. 3 the transmitter is represented at T. It consists of a polarizer at P, which is a Nicol prism; an analyzer at A, a Nicol prism like the first; and a glass tube T wound, with insulated wire,—all mounted on an optical bench. The Nicol prisms used are two fine specimens belonging to Dartmouth College, and obtained at a time when



Side.

Resistance of 4 coils in series	13.76 ohms.
Resistance of each coil	3.44 "
Resistance of 4 coils in parallel	0.86 "
Total number of turns on tube	2900 about.
Number of turns on each section	725

This tube was made of larger cross-section than necessary, and consequently consumed more power than would be required in another apparatus, but inasmuch as plenty of power was available this was not a matter of importance.

The four coils were usually connected in parallel in these experiments, with the object of reducing the inductance of the line, the inductance of the tube itself being reduced sixteenfold by this arrangement. Since a given strength of magnetic field had to be attained, the line current was therefore larger than it would have been with the coils in series. The current which was ordinarily used was about 17 amperes, which makes about $4\frac{1}{4}$ amperes around each coil of the tube, and the amount of power therefore required for the transmitter was about 249 watts. It must not be inferred that these figures represent what is necessary, but they gave good results. From ten seconds to half a minute is approximately the length of time that the current flows around the transmitter during the taking of an observation, and when, therefore, this amount of power is being used.

The diagram (Fig. 5) shows the transmitter circuit, including the tube at T with the four coils in parallel, a switch S, a dynamo D giving constant electromotive force of 110 volts, a bank of incandescent resistance-lamps Q, the line wires $L_1 L_2$, and the muzzle screen X_1. At $Y_1 Y_2 Y_3$ are represented the devices, previously described, for re-establishing the current. The line wires beyond are normally disconnected by the insulating plug inserted between the brass springs, so that the only path for the current before the gun is fired is through the screen X_1. The current is regulated by turning on or off lamps from the bank Q. The operation of the transmitter is as follows: When no

current is flowing in the circuit, the polarizer and analyzer are permanently set in the crossed position for darkness, and then, just before firing, the switch S is closed and the current flows through the circuit. This permits light to pass through the analyzer as long as the current is maintained. When the

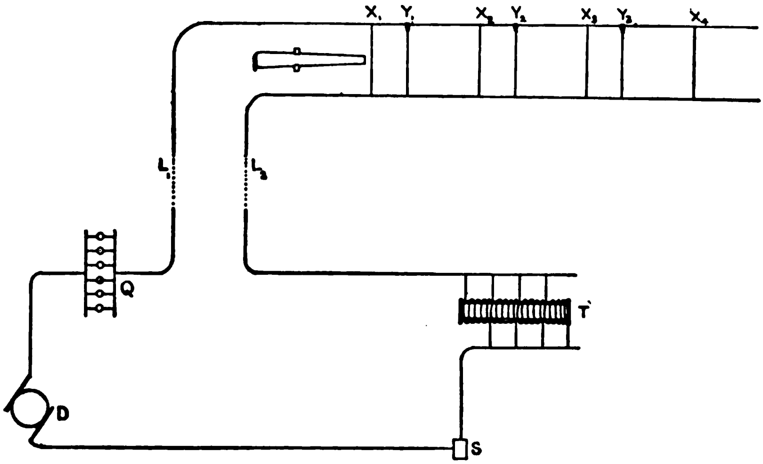


Fig. 5.—Transmitter Circuit.

projectile arrives at the muzzle of the gun the wires of the screen X_1 are broken and the current is completely interrupted.

[redacted]

camera containing a sensitized plate, which is shown in position ready for use at *C* (Fig. 3). Detailed views of the camera are shown in Figs. 6 and 7. It is made of wood in the shape of a rectangular box, the interior dimensions being 10″ high by 10″ wide by 2.5″ deep. Fig. 6 represents the front view of the camera-box *A* with the cover *B* removed, showing the small auxiliary dark chamber *C*, which contains the electro-magnetic device *D* with armature *E* attached to the brass spring *F* for releasing the camera-slide *G*. This slide is shown in the photograph, withdrawn from the grooves in which it normally slides by passing it through the opening at the top after removing the cover *H*. The narrow horizontal slit through which the light is admitted to the photographic plate is shown at *I*. The slit is constructed of sheet brass, the upper jaw being stationary, horizontal, and parallel to a radius of the photographic plate. The lower jaw *J* is a sector of sheet brass which slides between two guides, so that the lower edge of the slit is also parallel to a radius of the plate, and thus the slit is adjustable and is always a sector of the circular plate, the object being to obtain a uniform time of exposure for any part of the slit.

When the camera-slide is in position the nail at *K* rests upon the top of the brass spring *F*, and the upper edge *L* of the lower screen of the slide covers the slit *I*. When the current passes through the electromagnets by the binding-posts *M*, the armature is drawn and the slide released. The slit is exposed only while the opening in the camera-slide is passing by.

When the camera-slide comes to rest the upper screen *G* covers the slit, and it remains so covered. The upper screen *G* is capable of adjustment along the brass rods of the slide, and the opening between the upper and lower screen of the camera-slide is thus adjustable, and the time of exposure of the slit under control.

When the cover *B* is in position the space containing the slide and the release mechanism is a complete dark chamber in itself. A cap *N* in the cover *B* is removed just before the camera

is to be used. The wires shown at O are for the purpose of producing on the plate reference circles by casting their shadows. The entire back of the camera is removable, and its outside face is shown at P. Through the centre of the back a horizontal shaft O passes, which revolves in the bearing R.

Fig. 7 shows the inside of the camera; its body at A, the removable back at P, the slit at I, and the cover for the camera-slide at H. The slide is shown with the upper screen G removed. The inner end of the shaft is shown at Q, and the photographic plate S is mounted on this shaft. Suitable circular plates might easily have been obtained, prepared for mounting on the shaft; but rather than order special plates it was decided, on account of the limited time at our disposal, to adopt the following plan: Since the most sensitive plates were required, the Stanley plates (sensitometer 50) were used. The 8″ × 10″ size was cut into a circle 8 inches in diameter; and because it is not easy to make a hole in a glass plate which must be manipulated in a dark room, the circular plate was divided along a diameter T, and from each half a small central piece was cut to admit the shaft. When these two halves were mounted on the shaft, care was taken to fit them together accurately, so that the disadvantage of [redacted]

platinum point connected with the binding-post K was brought in contact with this spring, and the pressure was adjustable by a screw. Wires were led directly from the binding-posts H and K to some battery cells of the closed circuit type.

The motor available for running the camera was not exactly suited to the purpose. Four storage cells were used to energize the motor, and greater uniformity in speed was obtained by placing a heavy iron-toothed gear wheel as a fly wheel on the motor shaft, as shown at N (Fig. 3). This wheel also served another purpose in offering a convenient and ready means of determining the proper speed of rotation for a given setting of the camera slide. The wheel contained fifty-six teeth, and by simply holding on its periphery the edge of a card, with the motor running at an unknown speed, the corresponding note would be given out, and when this was compared with a tuning fork in the other hand of the observer, it indicated at once whether the speed of the motor should be increased or diminished. From the constants of the camera slide a curve was constructed showing complete vibrations given by the note on the fly wheel as abscissæ, and the corresponding opening of the camera slide in millimeters as ordinates, so that, if desired, the proper speed for any exposure becomes known, that is, a speed that will rotate the plate once during the exposure.

The Gravity Switch.—It was found necessary in the course of experiment to have an accurate means of exposing the camera at just the proper time in relation to the firing of the gun, and after some trials the form of switch shown in Fig. 3 at G was constructed with this object in view. It consisted of a wooden base with an upright brass rod in its center. On either side of this rod were two wooden uprights carrying the connectors $V V$ and $U U$. To these connectors were attached wire springs bent inward toward the brass rod. The weight W was a cylindrical piece of brass four inches long, with a hole drilled through it lengthwise so as to permit it to slide freely upon the brass rod. The gun was fired by dropping this weight down the rod.

When the weight arrived at the springs connected with $V V$ the electrical circuit was completed through $V V$, which operated the camera slide, and upon arriving at the springs connected with $U U$, the primer circuit was completed and the gun was fired. The interval of time between making the camera circuit and making the primer circuit could thus be varied within certain limits, by dropping the weight from different heights. The curve of calibration of this switch was constructed, which gives this interval of time for any height from which the weight was dropped.

The complete arrangement of the electrical circuits used with the different pieces of apparatus is shown in the diagram (Fig. 8), in which D is the dynamo; T, the transmitter tube; S, a switch which completed the circuit of the transmitter just a moment before firing the gun to prevent heating the coils; $L_1 L_2$, the line wires leading to the proving ground; Q, a bank of resistance lamps; $X_1 X_2 X_3$, etc., the screen wires shunted across between the line wires; $Y_1 Y_2 Y_3$, etc., the devices for restoring the current successively between the screens; and L and L' two 50 volt arc lamps in series, which for convenience were lighted by the same dynamo. The electrical tuning fork is controlled

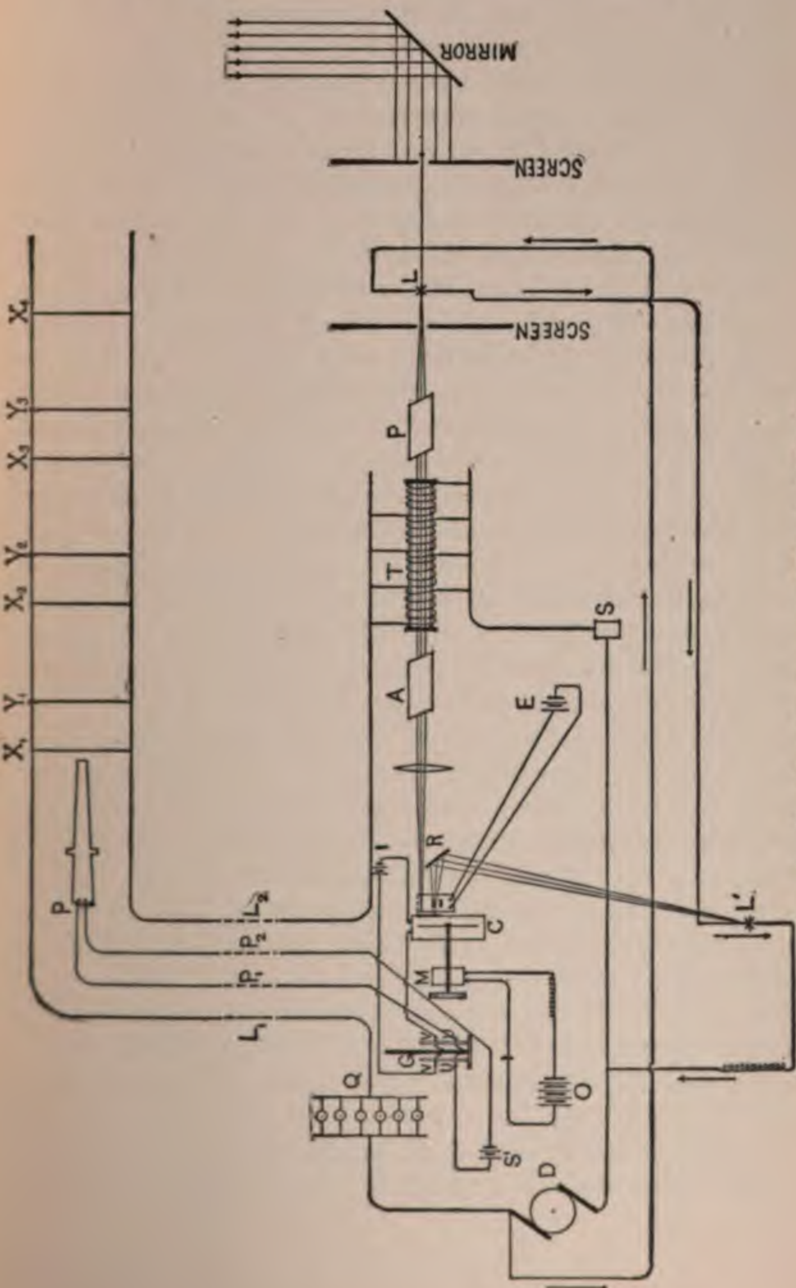


FIG. 8.—Complete Arrangement of Electrical Circuits.

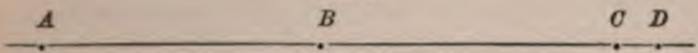
the best practical method of obtaining results. They were, of course, necessary as a preparation for this end, as any one who has had any experimental experience is fully aware. It seemed as though the instruments were just set up and sufficient practice in their use acquired to feel confidence in getting a result with every shot, when we were obliged to cease.

The construction of the camera used has already been explained. This design was adopted rather on the basis of expediency than because it is the most desirable form. There is one important feature of the camera, which was a decided disadvantage in experimenting, that would have been avoided by a different construction. We refer to the fact that the record must be made during a single revolution of the plate, and for this reason the whole time of exposure is but a small fraction of a second, about .066. The experimental difficulty introduced by this was to make the particular six-hundredths of a second, when the plate was exposed, coincide with the time when the record is made by the projectile, so that the beginning of its record should fall near the beginning of the exposure. A certain unknown time elapses after closing the primer circuit before the projectile arrives at the muzzle of the gun. If the plate were [redacted]

slide has to fall a small distance, about 1.1 cms., before the exposure begins. The armature also takes a little time to act, so that here again is an uncertain interval to be determined by experiment. It was not known whether the camera interval or the "firing interval" is the longer, and this determines whether the camera circuit or primer circuit must be closed first. It turned out by trial that to bring the muzzle record near the beginning of the exposure the camera circuit should be closed a small fraction of a second before the primer circuit.

To determine the "firing interval" above referred to, an experiment was tried as follows: A switch was used that would close the primer and chronograph circuits at approximately the same time. In Fig. 9 let time be measured along a horizontal

FIG. 9.



line, and let B represent the instant when both circuits are closed. An arrangement is attached to this same switch so that the camera circuit is made at some unknown interval previous to B, as at A. The beginning of the exposure of the plate occurs at some interval AC after A, and the arrival of the projectile at the muzzle at another interval BD after closing the primer at B. By reference to *Negative 8* (Fig. 10), obtained in one of the early trials, with this object in view, it is seen that the plate is exposed first at C. There are two circles of light; the outside at C is the chronograph record, and the inside at VW is the tuning fork record. The inside edge of one prong of the fork gave the wavy sinusoidal line VX, and the outside edge the line WY. The plate was exposed until it revolved to XY, when the camera slide cut off the light. Thirty-four complete waves may be counted on the plate, and as each wave occupies 1/509.46 of a second, the whole time of exposure is about .067 of a second. This interval will be found not to vary much in the different negatives. The line LM shows where the two

halves of the glass plate come together. The radial lines *H*, *I*, *J*, *K* were intentionally put upon the plate as lines of reference, though they proved to be unnecessary. To obtain them the camera was exposed in the dark room to an oil lamp when the plate was stationary, the slit being nearly closed for the purpose. This negative shows that the chronograph circuit was closed, and with it the primer made, at *B* some time before the plate is exposed at *C*, for the circle of light begins with the exposure of the plate. The light is cut off at *D* when the projectile cuts the screen at the muzzle of the gun, and the interval from *C* to *D* is approximately measured on the plate to be .041 of a second. This leaves us in uncertainty as to the whole interval *BD*, because the interval *BC* is unknown. We can say, however, that the interval from the closing of the primer circuit to the arrival of the projectile at the muzzle of the gun is certainly more than *CD* or .041 of a second.

Another trial made with this same object gave *Negative 13* (Fig. 11). It was attempted to bring the point *C* before *B*, that is, to have the camera exposed before the chronograph circuit is made; and at the same time care was taken not to shift its position so far that the point *D* would not be found on the

its constancy of position on the plate, we are ready to take records of the projectiles.

A word may be added by way of digression as to the nature of the light used. The two sources of light in the experiments were sunlight and arc light. The sunlight could not be depended upon when it was needed, but when available gave a smoother negative than the arc, as the light is perfectly steady. The arc light was much more convenient, as it was ready for use at any moment, but is not so steady as sunlight, or perhaps it ought to to be said that the lamps we were obliged to use were not so. It was fortunate that the arc could be used at all. This was a point which had not been determined until these trials were made. *Negatives 8* and *13* (Figs. 10 and 11) were made by arc light, and they show the variations in its intensity very distinctly, especially in the tuning fork record. At VW on *Negative 8* is a spot where the light was especially intense, and on *Negative 13* the radial streaks alternately light and dark are quite numerous.

The outside circle CD was made by light from the lamp L in Fig. 3, which passed through the transmitter. The tuning fork record was made by another lamp L', the light being reflected once from the mirror R. Two of the circles of reference, made by the shadows of the wires across the slit in the camera cover, as shown at O (Fig. 6), are seen at T and U on *Negative 13*.

Inasmuch as the variations of the intensity of the constant current arc show so plainly in the negatives, it may be of interest to show a record of an alternating current arc taken with this camera. This is seen in Fig. 12, which shows that the arc goes completely out and appears again at regular intervals. Twenty of these light spots appear on this plate during the time of exposure, which was about .067 of a second and two of these spots are made by one complete alternation of the current. Therefore the time of a complete alternation of the current is approximately $.067/10 = .0067$, and the number of alternations

per second is the reciprocal of this, or 149 is the frequency of the current furnished by the generator. It is noticeable that every other light spot is similar, but consecutive ones are different. The cause of this was a magnet held near the arc so that it was drawn out to the left when the current went one way, and to the right when it went the other.

The first trials to obtain a record of the projectile were made with an arrangement of circuits as in Fig. 13. It was intended to show the makes in the current, when the projectile passed between the pairs of points at *A, B, C, D* in succession. There was one screen X_1 at the muzzle to be used in the ordinary way as a break. It was hoped that when the projectile touched the pairs of points at *A, B*, etc., there would be time enough during the contact for sufficient current to flow to make its record on the plate, but on both the negatives 8 and 13 the muzzle record occurs and no trace of light is observed for the other points. To obtain the points for the projectile to bridge

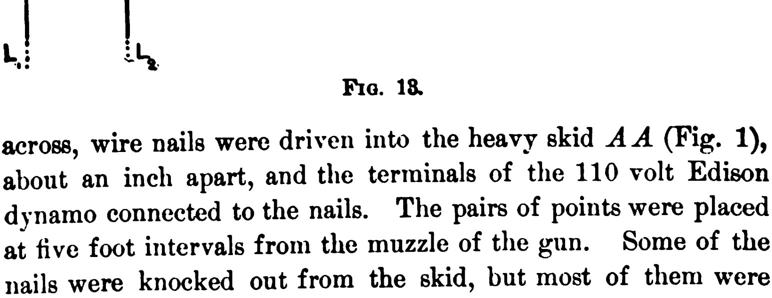


FIG. 13.

across, wire nails were driven into the heavy skid *AA* (Fig. 1), about an inch apart, and the terminals of the 110 volt Edison dynamo connected to the nails. The pairs of points were placed at five foot intervals from the muzzle of the gun. Some of the nails were knocked out from the skid, but most of them were bent over outwards and forwards by the projectile. As no light spots appeared on these plates, it proved that the inductance of the circuit was too great to permit sufficient increase of current

during the short time of contact to make a record. The inductance might have been reduced still more by the use of storage batteries instead of a dynamo, but these were not at hand. The inductance of the chronograph itself was decreased by winding the tube with several coils in parallel, instead of a single one in series.

The method of "makes" was finally abandoned for fear of losing too much time in experiment without obtaining any result, and the following plan adopted, when *Negative 10* (Fig. 14) was secured, and with it the first measurement of the velocity of a projectile. This was obtained on Saturday, Jan. 5, 1895, after eight of the fourteen days had passed. The plan was to use the break instead of the make, and the arrangement of circuits was essentially as in Fig. 5, but two screens being employed. The first screen X_1, consisting of only a single wire, was placed at a distance of the length of the projectile from the muzzle. The second screen X_2, consisting of only five wires about an inch apart, was 40.13 feet beyond the first. The device Y_1 for re-establishing the current was at a distance of ten feet from the first screen. Negative 10 shows that the camera was exposed at C for the transmitter record and at VW for the tuning fork. The muzzle screen was broken at X_1, the current re-established at Y_1, and interrupted again at X_2, when the projectile cut the screen X_2 (Fig. 5). Sunlight was used for this negative, and the light appears of a uniform intensity throughout. The waves of the fork are clearly seen, and the suddenness with which the light is cut off at X_1 and X_2 permits accurate measurements to be made.

As the plate revolves at a uniform angular velocity ω, the angle θ between X_1 and X_2 may be expressed

$$\theta = \omega t,$$

where t is the time occupied by the projectile in going 40.13

feet. The average velocity v of the projectile during the interval is then

$$v = \omega \frac{s}{\theta},$$

where s is the distance between the screens. In the present instance

$$\begin{aligned} s &= 40.13 \text{ feet}, \\ \theta &= 108^\circ\ 5'.815 \pm .444 \\ &= 108^\circ.0969 \pm .0074. \end{aligned}$$

The probable error is calculated from nine measurements of the angle, and shows that the angle θ can be measured with accuracy, the error being only .0068 of one per cent of the whole, or, again, an error of only one part in 14,630. This is not selected as an especially good example of the probable error, but is a fair case by which to judge the whole. Of course the percentage of error depends upon the whole angle measured, but 40 feet is a smaller distance than it is customary to use with other chronographs. Thus far the value of v is

$$v = \frac{40.13}{108.0969}\omega = .371241\omega.$$

The angular velocity ω of the plate is obtained from the record of the tuning fork. The advantage of some method of this kind for recording time will be apparent when it is considered that now the whole record is on each plate, and we are not troubled to take the speed of the plate at the time of firing the gun. In the experiments two tuning forks were used manufactured by Koenig in Paris, which were marked 1024 vs., that is, 512 complete vibrations per second. These were, as nearly as could be detected by the ear, exactly in unison. One of these forks was mounted to run electrically as previously described (see page 26). After mounting it was found to beat with the other fork just one hundred times in 39.45 seconds, or once in

.3945 of a second. This is the time which the other fork took to gain one complete vibration on the electrical fork, and in one second it would gain 2.535 complete vibrations on the electrical fork. As the higher fork makes 512 complete vibrations per second, the electrical fork therefore made $512 - 2.535 = 509.465$ complete vibrations per second. The accuracy of this method depends of course upon the determination of the absolute time of vibration of the fork. This has not as yet been made by us. Since it is not so important to determine the absolute velocity of the projectile in these experiments as it is to examine into the merits of the method, and see what might be done with a more perfect instrument, a determination of the period of the fork, and consequently of the angular velocity of the plate, aside from that made by the makers, is not deemed to be necessary before publishing the results of these preliminary experiments. Fortunately, however, we need not know the angular velocity absolutely in order to determine the relative velocity of the projectile at different points of its trajectory. This will appear later when other negatives are described, by which the relative velocity may be found with considerable accuracy.

The angular velocity of the plate is found by the relation

$$\omega = \frac{\theta}{t},$$

where θ is the angle through which the plate turns in the time t. The angle corresponding to 34 complete waves on *Negative 10* is found by measurement to be 294.54 degrees. The time of a complete vibration of the fork is the reciprocal of the frequency, or $\frac{1}{509.46}$ of a second. The time corresponding to 34 waves is therefore $\frac{34}{509.46}$, and the angular velocity

$$\omega = \frac{294.54 \times 509.46}{34} = 4413.42 \text{ degrees per second.}$$

This corresponds to about twelve and one quarter revolutions

per second, or seven hundred and thirty-five per minute. By substituting the value of ω in the preceding expression, we obtain for the velocity,

$$v = .371241 \times 4413.42 = 1638.5 \text{ ft. per sec.}$$

From the relations $v = \frac{s}{t}$ and $\theta = \omega t$ we may express the velocity as $v = \omega \frac{s}{\theta}$, in which form appear the three separate quantities that actually have to be measured to obtain the velocity. It has been shown that the angle θ can be measured with considerable accuracy, and with proper instruments it is evident that the angular velocity ω can be obtained with great accuracy. The distance between the screens can of course be found with some care to a high degree of accuracy; but when we attempt to express the distance by more than four or perhaps five significant figures, it is necessary to measure to a definite part of the wire of the screen. The uncertainty introduced here is caused by the conical point of the projectile striking the screens at unsymmetrical places, so that the distance may be greater or less than that which is measured by a small amount. This fact makes it useless to express more than four or five significant figures in giving the distance. The cause of the greatest error in expressing the velocity is thus the factor s in the above, so that we may say it is not the time interval which is so difficult to measure, but it is the space passed over by the projectile during this time.

The velocity of this same projectile was measured independently with the Boulengé chronograph, and was found to be 1615.8 feet at a distance of 81.10 feet from the muzzle, this being the distance of the point midway between the two large ballistic screens, one at 44, the other at 118.21 feet from the muzzle. This velocity reduced back from the mean point to the muzzle by Ingalls' tables gives a muzzle velocity of 1628.2 feet per second, as compared with the value 1638.5 obtained by us.

Negative 16 (Fig. 15).—The next purpose before us was the investigation of the *variation* in the velocity as the projectile leaves the muzzle of the gun, since experience had taught us that the blast was not to be feared as much as formerly supposed. With this object in view the plan was to obtain observations at several points along the trajectory. But to accomplish this it was necessary to make sure that the muzzle record could be depended upon to appear near the beginning of the exposure. For this the gravity switch described on page 27 was constructed. There were then arranged four screens at fifteen foot intervals, beginning with the muzzle screen. The muzzle screen was always placed in front of the muzzle a distance equal to the length of the projectile, so that the record would be made after the projectile is out of the bore. These screens were at distances 15, 30, and 45 feet respectively from the muzzle screen, and the arrangement of circuits similar to that in Fig. 5. Negative 16 was the first obtained with this arrangement, and arc light was used. The muzzle record at X_1 was delayed more than half a revolution of the plate; but the make at Y_1 and the break at X_2 were recorded. The make at Y_2, failed, and consequently all the rest of the record. The cause of this was found to be that the hard rubber wedge between the brass springs at Y_2 did not come out to allow the springs to come together. Although it was wedged in with only sufficient pressure to hold it and the attaching wire, yet the rubber was so brittle, the piece so thin, and the pull so sudden that it snapped off, leaving a small piece between the jaws. Finally, in trying different materials, instead of brittle rubber, hard sole leather was found to answer the purpose very well. The reason why the muzzle record occurred so late on the negative was decided to be due to the fact that the contacts in the gravity switch operating the camera rebounded from the weight as it fell, and thus delayed the exposure. This was remedied by fastening two flexible rubber cushions behind the springs to take up the rebound.

rty-two tuning fork waves on this plate correspond to 90° 25′. Therefore the angular velocity of the plate was

$$\omega = \frac{\theta}{t} = 290.416 \times \frac{509.46}{32} = 4613.0.$$

angle between the breaks is 41°.938, and this corresponds to ance along the trajectory of 15 feet. Therefore the velocity the projectile is

$$v = \frac{s}{t} = \omega\frac{s}{\theta} = 4613.0 \times \frac{15}{41.938} = 1649.9.$$

The Boulengé instrument gave a muzzle velocity for this shot of 1655 feet.

Negative 17 (Fig. 16).—Upon this negative obtained with arc light it is noticed that there is a record of the four breaks X_1, X_2, X_3, X_4, as well as the makes Y_1, Y_2, Y_3, which were all the points prepared in this trial. The measurement of the tuning fork record shows that 34 waves of the tuning fork occupy 305°.442, and therefore the angular velocity is 4576.8 degrees per second. Measurements on the negative give the following angles between the breaks X_1, etc., corresponding to the distances

s	θ
15	41°.213
30	81°.683
45	124°.267

Calculating the velocities for each point, using the muzzle screen as the first one in each case, we find

s	v
7.5	1665.7
15.0	1660.6
22.5	1657.3

The Boulengé record of this shot was 1655 for the muzzle.

Negative 18 (Fig. 17).—It was then arranged to obtain points at ten foot intervals instead of fifteen, and negative 18 was next obtained with arc light. This shows the muzzle break at X_1, the first make at Y_1, the ten foot break at X_2, the make Y_2, and the twenty foot break X_3; but that is all. The reason why the rest of the record does not appear is supposed to be because the next make, Y_3, came so late that the following screen X_4 was broken before the current was made, and thus there is no record.

This is seen to be almost the case at Y_2, where the make was only just in time to be recorded before the break X_3 came. From the result of eight different measurements of each angle on this plate we find the following relation between s and θ:

s	θ
10	25° 33′.25
20	51° 30′.44

The angular velocity of this plate was $\omega = 4312.10$, an angle of 349°.1676 corresponding to 32 waves on the negative. If the velocity is measured by means of the muzzle and ten foot screens, we have $v = 1687.4$ for a point half way between, or five feet from the muzzle. If we count from the muzzle to the twenty foot screen, we have $v = 1674.3$ for the velocity at ten feet. The velocity at fifteen feet may be obtained from the ten and twenty foot screens. It is 1661.5 feet. We may tabulate as follows:

s	v
5	1687.4
10	1674.3
15	1661.5

This clearly shows a decrease in the velocity as we recede from the muzzle, but there is no indication to show whether the decrease began before or after the projectile passed the five foot mark. The velocity is also so variable near the muzzle that it is not nearly correct to say that the average velocity between zero and ten feet is the actual velocity at five feet.

Negative 19 (Fig. 18).—This same arrangement of circuits was tried again, except that the devices to close the circuit were brought forward and placed nearer to the preceding breaks. Arc light was used, and the record gave every point complete at intervals of ten feet, except the last one, which was only *five* feet, making in all six points in forty-five feet from the muzzle. The results of measurements on this plate are given in the following table:

s	θ
10	28°.098
20	56°.504
30	85°.016
40	113°.446
45	127°.793

As the tuning fork record on this plate is not distinct enough to read, we may assume that the muzzle velocity is as measured by the Boulengé chronograph, viz., 1628.2. The velocities are given in the following table, each value being calculated from the muzzle screen:

s	v
5	1628.2
10	1619.4
15	1614.6
20	1613.2
22.5	1611.3

It may be of interest to note that the radial lines H, I, J, and K on this plate show the actual width of the slit used.

Negative 20 (Fig. 19).—Screens were now placed at intervals of only five feet, from the muzzle to a distance of 45 feet, and also the further large ballistic screen was used. This negative showed that the make devices were not placed sufficiently in advance of the succeeding screen, as the record shows only a few points, and then the current was made just in time. Although the devices were placed immediately after the preced-

ing screen, yet the projectile would reach the next screen before the current was made. This showed that it took about .003 of a second, or the time it takes the projectile to go five feet, for the springs of the make device to come together. This time varies with the strength of the springs and the width of the insulating wedge. The light appears again at the make after the 45 foot screen, and the screen beyond was 118.2 feet from the muzzle, so that its record did not appear before the light was cut off by the camera slide at P. Sunlight was used for this negative.

Thirty-five waves on the plate correspond to 302°.10, and the angular velocity is therefore $\omega = 4397.4$. The relation between the space and angle θ are given in the following table:

s	θ
10	26° 3′.5
15	39° 1′.0
20	52° 10′.2

The velocities calculated from the muzzle screen are:

s	v
5	1687.5
7.5	1690.6
10.0	1685.8

This shows that there is an increase in the velocity indicating a maximum point somewhere between five and ten feet, but probably nearer five than ten.

Negative 23 (Fig. 20).—The tuning fork record was not recorded upon this plate, so that the exact time of rotation is not known. This can, of course, make no difference in the relative velocities indicated by the relative spacing of the different breaks, and can only affect the absolute velocity, about which we are not so much concerned. The Boulengé chronograph also failed to obtain a record of this shot. A very close estimate may be made, however, by comparing the dark space (or light space) on this

negative with that on negative 20, since the whole time of exposure of each is alike. Such a comparison gives for the angular velocity of this plate 4421.3. The corresponding values of *s* and θ are shown in the following table. This is the first negative obtained in which all the points at five foot intervals up to 45 feet from the muzzle are recorded.

s	θ
5	13° 49′.29
10	27° 19′.29
15	40° 53′.79
20	54° 36′.00
25	68° 24′.83
30	82° 28′.25
35	— ——*
40	110° 10′.46
45	123° 50′.88

The velocities found by considering the muzzle screen to be the first screen are shown in the following table:

s	v
2.5	1599.4
5.0	1610.8
7.5	1621.7
10.0	1619.5
12.5	1615.6
15.0	1608.3
17.5	——
20.0	1605.3
22.5	1606.5

This table is also exhibited graphically in Fig. 21, and shows that the velocity suddenly increases within a distance of six or eight feet from the muzzle of the gun, and beyond that point gradually diminishes. The uneven appearance of the line is due

* This record fell upon the cut in the plate, and could not be accurately measured.

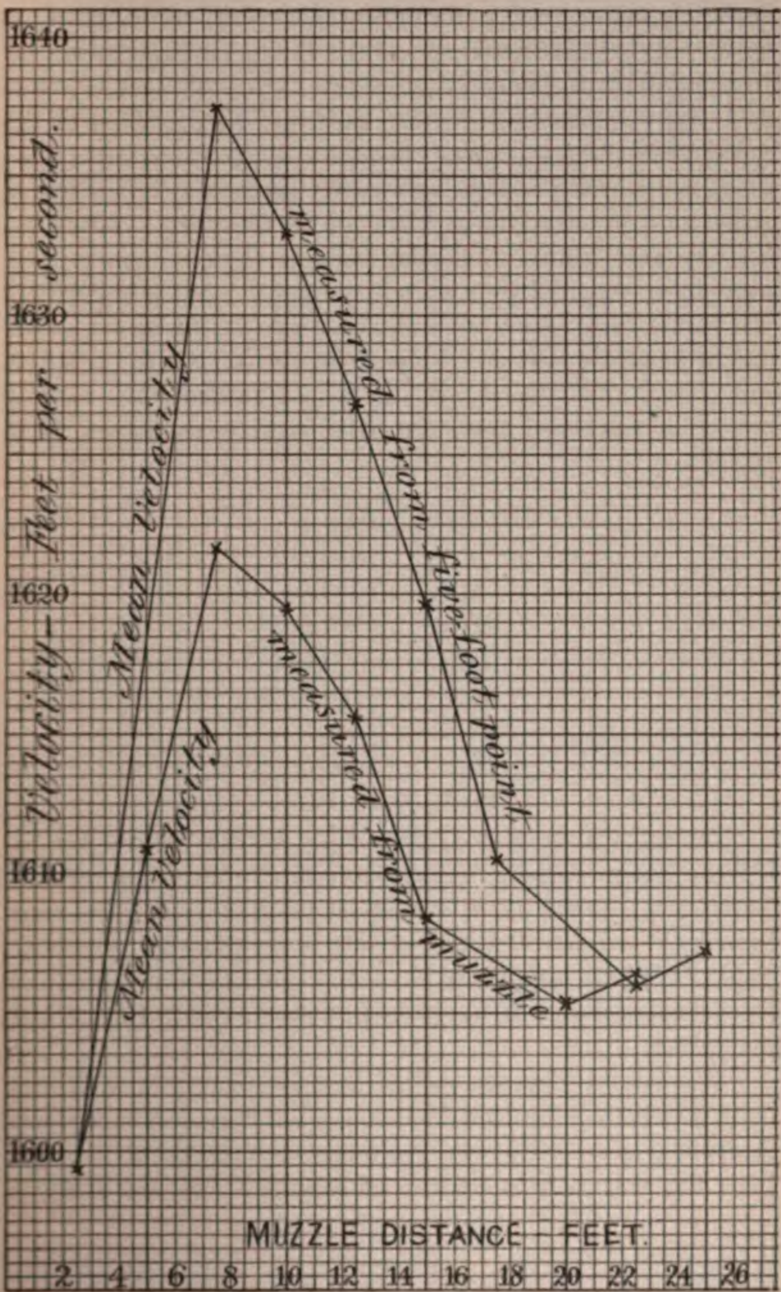

1640
1630
1620
1610
1600
Velocity— Feet per second.
Mean Velocity
measured from five-foot point
Mean Velocity
measured from muzzle
MUZZLE DISTANCE - FEET.
2
4
6
8
10
12
14
16
18
20
22
24
26

FIG. 21.

to errors, not so much in measuring the record on this plate, as to the fact that the breaks of the circuit did not occur at exactly five foot intervals, since the point of the projectile does not strike each screen in exactly the same manner. The increase of the velocity after the projectile passes from the gun is so large, however, that it is not hidden by errors. Every negative obtained shows an increase at the beginning of the trajectory. Since the velocity does increase for some distance from the muzzle, the average as measured from the muzzle screen must be less than if the point from which we measure were the maximum point. Let us therefore make a table of velocities, taking the five foot screen as the first instead of the muzzle screen. The table of velocities, calculated from the same readings as before, is as follows:

s	v
2.5	1599.4
5.0	1637.5
7.5	1633.0
10.0	1626.8
12.5	1619.7
15.0	1610.5
17.5	——
20.0	1606.0
22.5	1607.3

This table is represented graphically by the broken line labelled "mean velocity measured from the five foot point." This shows that the actual velocity at the maximum point must have been at least 1637.5, and this is considerably more than would have been assigned is the calculation had been made from the muzzle screen. It would in that case be only 1621.7 feet per second.

Negative 25 (Fig. 22).—This negative was taken with sunlight, and besides being the last one taken, proved to be the best. It contains a record of the projectile at intervals of five feet from the muzzle to a distance of forty-five feet, and includes

also a screen at a distance of ninety-five feet. At this stage in the experiments the apparatus was just getting into such shape that we could depend upon it to give results every time, when it became necessary to stop. Measurements on this plate are given in the following table. Each angle is determined from as many as eight measurements, and the mean taken.

s	θ
5	13°.443
10	26°.525
15	39°.802
20	53°.123
25	——
30	79°.648
35	92°.940
40	106°.361
45	119°.827
—	——
—	——
95	253°.900

If velocities are calculated from the above table, regarding the five foot screen as the first each time, we find the following table of velocities. The velocity at a distance of seventy feet is an exception to the above, the 45 and 95 foot screens being used for the 70 foot point.

s	v
2.5	1635.8
7.5	1681.0
10.0	1668.6
12.5	1662.8
15.0	——
17.5	1664.8
20.0	1663.6
22.5	1656.7
25.0	1653.7
50.0	1646.2
70.0	1640.2

This table is exhibited graphically in Fig. 23, and shows a distinct rise in velocity after leaving the muzzle, which gradually falls off later. The irregularities in the points are no greater than in Negative 22, but the correspondence between the two negatives is quite marked. The rise in velocity is nearly the same in each, and the maximum point occurs at approximately the same distance from the muzzle.

These results may be otherwise exhibited. If a curve is drawn representing the relation between the space and time (or what amounts to the same thing, the space and angle θ which is

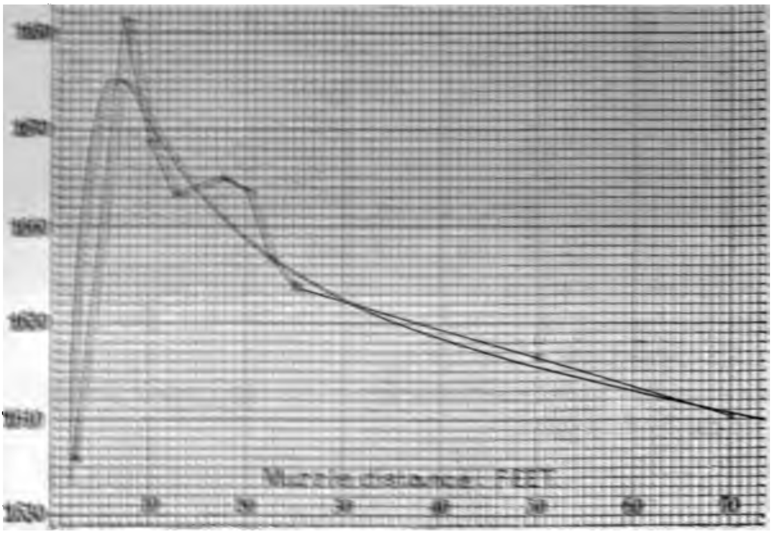


Fig. 23.

proportional to the time) found in the table above, then we might find the velocity at any point by measuring the tangent of the angle which a tangent line makes with the axis of time because of the relation $v = \frac{ds}{dt}$. In Fig. 24, if the points given in the table are located according to the scale there indicated, they will be found to lie very closely upon the diagonal line

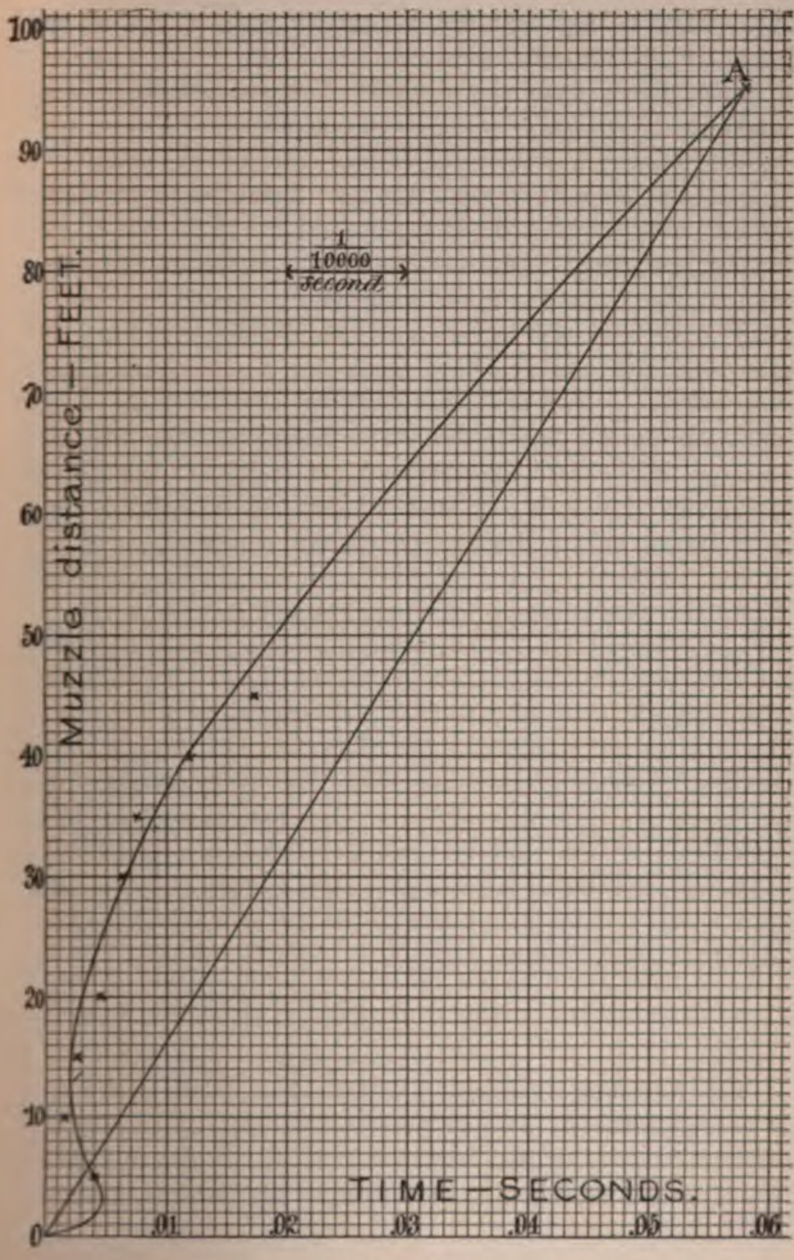

100
90
80
70
60
50
40
30
20
10
0
Muzzle distance — FEET.
A
1/10000 second
.01
.02
.03
.04
.05
.06
TIME—SECONDS.

FIG. 24.

OA. They do not, however, lie exactly upon it, and all the points beyond the first lie to the left of it. If the distances of these points from the diagonal line are magnified one-hundredfold (so that two large squares correspond to one ten-thousandth instead of one-hundredth of a second) the points will be located as they are in the diagram. For example, the point opposite forty-five feet lies about two squares to the left of the diagonal line, which means that the time in coming to the forty-five foot point was one ten-thousandth of a second less than it would have been if it were exactly on the diagonal line. A curve is drawn passing within the limits of error through all these points, in such a manner that the tangent of the angle which the tangent line to this curve makes with the time axis when properly translated, represents the velocity in the former curve, Fig. 23. It is seen that the point of inflection in this curve occurs at the position of maximum velocity, and the velocity increases up to this point, and then gradually diminishes again, as it is observed that the tangent then decreases.

The instrument used to measure the angles on the negatives is a large spectrometer, with a graduated circle reading directly to ten minutes of arc, and with the verniers to ten seconds. The two halves of the negative were fastened down upon a piece of plane glass, and the whole laid horizontally on the turning table of the spectrometer. The negative was supported upon blocks so that the light could be reflected up from below, and it was centered by means of the circles of reference on each plate. The settings were made by the use of a stationary telescope having cross-hairs.

CONCLUSION.

The foregoing experiments described in detail justify one or two conclusions: This chronograph as thus far developed, although home made and hastily assembled, has clearly demonstrated its important field of usefulness for the accurate measure-

ment of small intervals of time. The record made by a break in the current due to the passage of the projectile is sharper and more defined than we had anticipated, and this permits of an accuracy in reading the record even beyond that attainable in measuring the intervals between screens on the proving-ground. A future working instrument designed upon this fundamental principle is capable of endless modification, and an instrument properly designed would be as simple in its operation as any of the well known chronographs now in use. The whole is manipulated by a single switch, which fires the gun and obtains the record.

The adaptability of this instrument for obtaining observations at any number of points of the same trajectory and the nearness which these points may have to each other, make it admirably suited to the study of the law of change of velocity near the muzzle of the gun, and also to the systematic study of the law of the resistance of the air to projectiles of various forms; problems which, since the advent of the modern high power gun with its realm of velocities unthought of in the classic experiments of Bashforth, are at present of paramount importance to the science of *exterior ballistics.*

The principal ballistic result obtained from these experiments may be said to be the locating of a maximum point in the velocity curve outside of the gun. This maximum point is, in the case of the gun and conditions of loading described, at six or seven feet from the muzzle of the gun—certainly more than five feet and less than ten—or about 25 calibers in front of the muzzle. The increase in velocity from the muzzle to the maximum point is large—more than 40 foot-seconds. The muzzle velocity being about 1600 feet, this increase is about 2.5% of the whole.

The decrease in velocity beyond the maximum point is comparatively gradual, obeying the true law of the resistance of the air so that the projectile must travel about a hundred feet be-

fore the velocity is reduced to that which it actually had at the muzzle.

This maximum point introduces an error in the present method of obtaining muzzle velocities in which the velocity is measured at a distance of one hundred to two hundred feet, and reduced back to the muzzle by formulas.

The direction of this error is shown in the diagram, Fig. 25. Supposing that the heavy line represents the true velocity curve, the part beyond the maximum point *M* would follow the law of the resistance of the air, and by reducing back by formula the law of air resistance is assumed to be continuous to the muzzle. This would extend the velocity curve corresponding to formula back of the maximum point, as indicated by the dotted line, to *A*. The diagram measures velocities from a

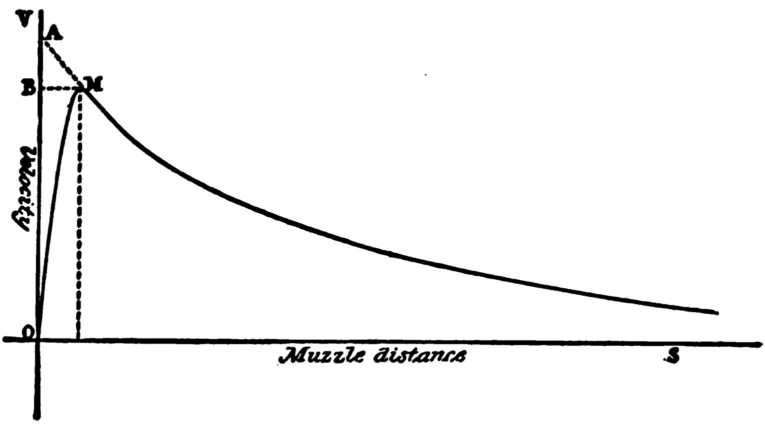


FIG. 25.

horizontal axis much below the axis represented, the increment of velocity above the actual muzzle velocity alone being represented. The diagram shows that the computed velocity for the muzzle is greater than the actual muzzle velocity by an amount OA, and also greater than the *maximum velocity actually attained by the projectile* at M by the amount AB.

The determination of the law of development of velocity

inside the bore of a gun has been the subject of investigation by two general methods. The first is that originally employed in 1760 by Chevalier D'Arcy, and recently in Paris by Mr. L. V. Benet, an account of whose experiments is given in the *Journal of the United States Artillery.** Successive lengths are cut from the chase of the gun and the velocities measured for each artificial muzzle. The second method consists in piercing the chase at intervals and observing the velocities with a chronoscope such as Noble's. It need not be stated that any method which would permit reliable interior velocity curves being taken without the mutilation of the gun must surely be a distinct advance. Upon the data which such curves would furnish rest not only the questions of gun construction, but also the ready study of new powders and their adaptability to existing ordnance.

A few preliminary experiments were tried with a view of determining the value of this instrument for the measurement of velocities inside the bore, but any mention of them is withheld until further experiments can be made. The time at our disposal was so limited and so many difficulties had to be overcome on account of the most inclement winter weather, and the necessity of improvising all apparatus on the ground, that it was decided to devote all disposable time to problems outside the bore.

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* Vol. I, No. 3—*A study of the effects of smokeless powder in a 57-mm. gun.*

EXPERIMENTAL DETERMINATION OF THE MOTION OF PROJECTILES INSIDE THE BORE OF A GUN WITH THE POLARIZING PHOTO-CHRONOGRAPH.

In the previous paper were described some preliminary experiments with the Polarizing Photo-chronograph applied to the measurement of the velocity of projectiles outside the bore of a U. S. 3″.2 breech loading field rifle. The results of these experiments being submitted to the Board of Ordnance and Fortification, a chronograph built upon this principle, making use of polarized light, was authorized, and the construction of the same intrusted to our care.

Since the original experiments were more of the nature of a laboratory investigation than suited to the practical needs of the military service, it became our first purpose to perfect the details of the instrument by further experimentation, in order to avoid hastily assembling for the Government an instrument which, when completed, would manifestly be capable of great improvements. Accordingly the experiments to be described below were carried out at the U. S. Artillery School during the month of August, 1895.

The immediate objects of these experiments were twofold. First, to perfect a practical chronograph upon this principle, suited to the needs of the military service; and second, to deter-

mine the adaptability of this instrument to the study of the motion of projectiles inside the bore of a gun.

There was, at the outset, no reason to doubt that this chronograph could be employed, as Noble's or Schultz's chronoscopes formerly have been, to determine interior velocities in cases where the gun might be mutilated by piercing holes along the bore at intervals, and inserting electric circuits to be interrupted by the projectile as it passes. Yet the usefulness of such a method is so insignificant compared with any plan which would enable interior velocities to be measured at any time, and in any gun, with almost as great ease as exterior velocities may now be obtained, that it became our purpose to search for such a method. Although the time as yet available for this work has been very limited, and the constant pressure of other duties prevented anything but a superficial examination of results, yet it is thought that sufficient success has been attained to warrant this early presentation of an account of the experiments thus far conducted. The observations themselves which are presented are of secondary importance compared with the method outlined, since they may easily be confirmed or disproved by future trials.

A superficial study of the history of interior ballistics cannot fail to convey the impression that the whole number of experiments giving reliable data is very small indeed, and those which are the most reliable have been worked over and over again, involving much labor which might profitably have been directed toward obtaining new experimental evidence. The elaborate preparations and great expense hitherto involved in carrying out such experiments have confined them to select ordnance committees backed by governmental aid, and are in a great measure responsible for the meager experimental data available.

In presenting the results of any physical experiments it is deemed of first importance to insist upon having the *original observations* given independent of any derived results, no matter how elementary the process of derivation. Unfortunately this principle has not been observed in many of the memoirs upon

which we must depend; and, furthermore, the omission to state exactly from what experiment, or set of experiments, certain measurements are derived greatly depreciates their value. In deciding upon a method of presentation of the results of this work, we were confronted at the outset with the generally accepted theories from which our superficial observations indicated some radical departures, and we had on this account some hesitancy in making any presentation at present, until further experiments could be conducted. It was our desire to test the well known formulæ which are ordinarily applied; but since no formula in use was found to represent the experiments, and those available were *derived* formulæ expressing the relation between the travel and velocity or pressure but not between the travel and the time, which the observations themselves give, it was decided to give the results of measurements for each shot separately, as a physical experiment independent of any previous theory.

Historical Sketch.

Two general physical methods have been employed in experimentally determining the pressures developed in the bore of a gun, viz., the Statical and the Dynamical method. In the former class come the early experiments of Count Rumford in 1792, General Rodman's cutter gauge and that of Colonel Uchatius, and Noble's crusher apparatus. In each of these cases the force which holds the powder gas in equilibrium is recorded and measured. The dynamical method of experimenting consists in investigating the motion of some body connected with the gun system so as to be under the influence of the expansive force of the powder gas, and, from the circumstances of this motion, to pass by calculation from known laws of dynamics to the pressures required to produce such motion. In the application of this method we find that study has been made of the motion of pistons, bullets, etc., caused to move by the products of decomposition, in a direction perpendicular to the axis of the

bore; of the motion of the gun itself during recoil; and finally by investigating the motion of the projectile during its passage through the bore. In 1845 General Cavalli applied at various distances from the bottom of the bore of a 12-pounder smooth bore field gun a series of small musket barrels of wrought iron arranged to throw spherical bullets under the action of the powder gases against a ballistic pendulum placed outside the gun, by which the initial velocities of the bullets were measured.

It was assumed that the quantity of motion communicated to the bullets at the different points along the bore is a measure of the force of the powder gases at the corresponding sections of the walls of the gun.

An improvement upon this method was that adopted by the Prussian Artillery Committee in experiments conducted in 1854.* In these experiments a short gun barrel was screwed into the wall of the gun opposite the center of the powder chamber, and cylinders of varying mass ejected from it by the action of the powder gases. By thus varying the mass of the pistons it was possible to vary the time of the action of the gases upon them, and from a knowledge of the velocity of projection of the cylinders as before, the pressures could be deduced, not only for the chamber itself, but also at different points along the bore. In this same class are included the experiments in France with the accelerometer and the accelerograph of Marcel-Deprez, in which, as before, the powder gases actuate a piston which is made to move a known weight a certain registered height along a spindle, from which the velocity of the piston can be calculated, thus avoiding the great practical inconvenience of an exterior apparatus, which must remain properly placed during the recoil of the gun, for measuring the velocity of the piston.

By knowing the spaces passed over by the gun in the direction of the axis of the bore, it is possible to deduce the law of

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* Archiv für die Offiziere der Koeniglich Preussischen Artillerie und Ingenieur Corps.

Revue de Technologie Militaire.

change of pressure against the bottom of the bore. General Rodman was the first to construct a recoil velocimeter. The French Marine Artillery use the Sebert velocimeter, which consists essentially of a vibrating fork held in position, and describing the law of spaces upon a blackened steel ribbon which moves with the gun.

In all the dynamical methods thus briefly mentioned, besides being dependent in each case upon certain arbitrary assumptions as to the nature of the action of the gases upon the piston or other body as compared with its action upon the base of the projectile itself, they are open to the general physical objection that the desired data are derived and not directly observed.

In other words, a fundamental rule of physical investigation requires the experimenter to direct his energy upon the study of the thing itself, when possible, in preference to observing other phenomena connected thereto and obtaining the desired result by processes of derivation. This fact of itself especially commends all dynamical methods which are directed to the observation of the law of motion of the projectile in preference to any auxiliary body, for we may be sure that the more complete our knowledge of the motion of a projectile during its passage through the bore, the more nearly can we approximate to the true law of change of pressure upon its base and the walls of the chase adjacent thereto.

In 1760 Chevalier D'Arcy calculated the pressure of the powder gases at different sections of a musket barrel by successively shortening the length of the barrel and measuring the initial velocity corresponding to each length. This same method has been successfully tried by several experimenters in recent years, notably the excellent experiments of Mr. L. V. Benet of the Hotchkiss Ordnance Co., Paris. The registering projectiles of Colonel Sebert for large calibers also represent one method of attacking the problem in a general way.

Another method has for its basis the determination of the times required for the projectile to pass over known distances

along the bore. The experiments conducted upon this principle have employed chronographs specially constructed for the purpose, and have operated by causing a record of the instant the projectile reaches certain points along the bore to be secured by the projectile interrupting an electrical circuit at each of the prepared points. Notably among these experiments have been the classic work of Noble and Able employing the Noble Chronoscope; the experiments carried out by General Mayevski in 1867 at the Krupp factory in Essen; and the variations of the method employed in France using the Schultz Chronoscope.

Various attempts* have been made by the French Marine Artillery to record the passage of a projectile through the bore without mutilating the gun. In 1876 a method was tried in which a wooden rod of sufficient length to extend beyond the muzzle was attached to the projectile. On its extremity was fixed normally a sheet iron disk, which, in the movement of the projectile, encountered successively interrupters placed on a strong wooden rule parallel to the axis of the gun, in front of the muzzle, and fastened to the chase of the piece by strong iron collars. The distances were measured along the rule and the times by a chronograph. This arrangement, which might answer for a gun of small length and a low velocity, failed with high velocity and a rifled gun. A better method has been found in the employment of interrupters glued in the bore, proposed by Mr. Letard. These interrupters, which may be placed in the bore to the number of five or six, are secured one after another by means of common resin. They are set in position by an expansion rammer with a movable wedge similar to those used for taking impressions of the bore with gutta percha. The insulated conducting wires attached to each interrupter pass out the muzzle to the chronograph. The devices being in place, their positions are determined by a measuring rule inserted at

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* **Extraits du Memorial de l'Artillerie de la Marine.**
U. S. Ordnance Notes No. 313, by H. Sebert.

the muzzle. A difficulty experienced in this method was that the first interrupters and wires in being ejected were liable to strike the succeeding ones before the arrival of the projectile, and thus give a false signal.

The Improved Instrument.

In the previous paper a full description of the instruments used was given. Many important improvements, however, in details which add to the efficiency of the instrument, were developed during the progress of these experiments, although no change was made in any essential principle. The month of July was devoted to various necessary preparations to facilitate experimenting, which proved a great saving of time in the end, such as installing a suitable storage battery, constructing a universal mercury switch board, testing different carbon bisulphide tubes, perfecting tuning fork records, securing and testing a good projection lamp, etc. One of J. B. Colt's projection arc lamps was tried in the hope that a light might be found which would not show such variable illumination when subjected to the instantaneous test as those formerly used had done. The illumination obtained even with such a sensitive test as was applied remained perfectly steady, and compared favorably with sunlight, as a reference to any of the records will show. Having obtained a perfectly satisfactory source of artificial light energized by a storage battery, the great advantage over sunlight, in being always ready, need hardly be mentioned. Naturally the subject of sizes and forms of glass tubes for the carbon bisulphide, and the manner of obtaining the requisite ampere turns, were matters of early consideration, and several tubes were obtained for test. It was found that, by introducing a condensing lens immediately in front of the arc, a greater intensity of light was obtained upon the plate than formerly.

One of the most unsatisfactory features of the original instrument was the small amplitude of the waves of the tuning fork,

and special attention was given to improving this. The diagram (Fig. 26) shows the principle of an improved method of obtain-

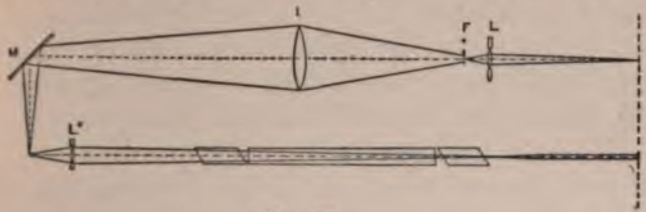

FIG. 26.

ing a fork record, which gave beautiful results and greatly increased the possible accuracy of such records. While the plan of optically magnifying the amplitude of the waves had already been successfully accomplished by us, yet the idea of further increasing the accuracy of such records had been beautifully carried out by Lieutenant B. W. Dunn, Ordnance Department, U. S. A., in some experiments which have unfortunately not yet been published.* The same arc lamp was used for both the chronograph and tuning fork records. A plane mirror *M* reflected the light through a condensing lens *L* upon a thin piece of aluminium foil glued to one prong of the fork *F*. In this foil was a smooth round hole about one millimeter in diameter. A lens *L'* focused this brightly illuminated hole as an object upon the sensitive plate, and at the same time magnified it to about six millimeters. The fork was excited by drawing a wedge from between the prongs in preference to using any electrical method, as this was found to be convenient and satisfactory.

When one prong of a fork is allowed to cast its shadow through a narrow slit upon a moving plate, the result is that a single sinusoidal line divides the region of light from the shadow of the fork. At the same time the other edge of the fork gives

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* The account of these experiments, which has been published since this paper was written, may be found in Notes on the Construction of Ordnance, No. 71, also Journal of the U. S. Artillery, Jan.-Feb., 1897.

another similar sinusoidal curve which is ordinarily separated from the first curve so as not to interfere. By having two slits near together, one above another, a second shadow would fall on the plate having an exactly similar wave for its boundary, but it would lag behind the first wave by an amount depending upon the speed of the plate and the distance between the slits. This would therefore intersect the first wave at regular intervals of a wave length, and by the points of intersection make it possible to measure with great accuracy the value of a wave length. Instead of having two slits, the same object was attained by allowing the illuminated image of the magnified hole in the piece of aluminium attached to the fork to fall upon the plate. Those parts of the image which fell somewhat behind the rest gave waves differing in phase with the other part, so that results like those exhibited in Figs. 27, 28, and 29 were obtained. It is noticed that a cone of darkness intersects a cone of light, the dark region having had no exposure, and the light cone, so to speak, a double exposure. The fine circular lines seen are shadows cast by ordinary hairs fastened across the slit. They serve merely as reference circles by which the center of revolution may be accurately found. To allow the whole area of the magnified image of the illuminated hole to fall upon the plate, a square hole of suitable size was cut through the jaws of the camera slit opposite the point where the tuning fork record was to fall.

Method of Experimenting.

After considering a number of different ways to measure interior velocities without mutilating the gun, that seemed to be the more promising, with the instruments in hand, which had for its fundamental idea the extension of the projectile forwards in the bore by some rigid body attached thereto, and measuring the motion of this prolongation, assuming that it is the same as that of the projectile. The first trial of this kind was made on

August 2, 1895, and proved to be unsuccessful. A wooden rectangular rod, tapering towards the muzzle, was pivoted by a brass cap on its base upon the point of the projectile, and it was expected that the projectile would turn in the rifling without turning the rod, which was guided between two vertical supports fastened to the muzzle. Two long pieces of spring steel were firmly fastened to a wooden collar upon the muzzle. The ends of these were bent inwards to bear upon opposite sides of the rod about a foot in front of the muzzle. Strips of thin copper were fastened along the narrow edges of the rod at determined intervals on opposite sides, and electrically connected together in pairs. In position before firing the current is made, and passed from one spring through the first pair of copper strips on the rod to the second spring. When the projectile moves forward the springs first pass off from the copper upon the wood and break the circuit, and then on to the next copper strips, restoring the circuit again, and so on. The intervals along the rod between breaks are measured, and the times between the corresponding breaks ascertained by the chronograph. In the trial with this device the record of the first break was observed, but no succeeding make or break was recorded. Among other causes the chief difficulty seemed to be due to the blast preceding the projectile, which raised the brushes off from the rod not to return again, though the springs were fairly strong.

The next attempt, on August 7th, was a device designed to utilize the blast, and make it aid rather than prevent the contact of the brushes upon the rod. A view of this arrangement just before firing is given in Fig. 30. The rod in this case was made cylindrical and rigidly attached to a shrapnel projectile by taking out the fuse and screwing in the rod up to a shoulder. Its total length was about seven feet, and its diameter an inch and a quarter. The copper strips in this case were wrapped around the rod and sunk into the wood flush with the surface. The interval from first to second break was 35.6 cms., and from second to third 106.5 cms. The brushes were made

of sheet steel bent to a V shape and screwed to brass rods, at A and B in the figure, which served as hinges. The blast in pressing against the brushes encounters two surfaces on each brush inclined at such angles that the moments of rotation about this hinge oppose each other; but the outside surface of each brush was longer than the inside, as shown, to make the resultant moment cause the brushes to press against the rod instead of separate from it. The record of two points at 0 and 35.6 cms. given by this apparatus was the first obtained in interior velocities, but the last and only other point prepared did not appear on the chronograph record.

Weight of shrapnel projectile prepared to receive the wooden rod	12 lbs.	4	oz.
Weight of wooden rod	1 lb.	14	oz.
Total	14 lbs.	2	oz.
Weight of charge (without sack)	3 lbs.	$12\frac{3}{4}$	oz.

The result of this shot seemed to show that the difficulty experienced was in keeping two brushes in continuous electrical connection with the rod as it passed out. The centrifugal force due to the rifling also has a tendency to cause the rod to be displaced from the brushes. The rod being worked by hand was consequently not an accurate cylinder, and the inequalities due to this cause became greatly magnified with such high velocities. By the preceding experiments it appeared necessary to have an accurately round rod and a *single* brush if possible.

Electrical Contact between Gun and Projectile.

The plan of using a single brush became more and more attractive, and a solution of the problem depended upon whether the projectile in passing out of the bore maintained throughout uninterrupted electrical contact with the gun itself. Accordingly the next step was an experiment to determine this question.

On the afternoon of the same day, August 7th, this experiment was carried out, and indicated that such an electrical connection *is maintained* during the passage of the projectile through the bore. A shrapnel shell was fitted with a round $\frac{1}{8}$-inch thick brass disk of slightly less diameter than the bore, placed upon the flat nose of the projectile and secured by screwing in the fuse. An insulated wire was attached to the nose of the projectile and passed out at the muzzle. The object of the flat disk was to prevent the projectile from running over the wire and prematurely cutting it before the projectile left the muzzle. The rifling of the gun was very thoroughly washed with water, and the projectile polished in a lathe until it was bright. The two line wires from the chronograph were joined respectively to the projectile and gun. To secure contact with the gun the rear sight seat was removed and its screw served as a binding-post. A make device described in the previous paper was placed at a determined distance in front of the muzzle, and the terminals of the chronograph also extended to it. The object of this additional circuit was to determine where the interruption of the current by the projectile in its passage occurred—whether near the seat or near the muzzle. This may be done by estimating the time between the break and the succeeding make on the negative, and noting the corresponding distance on the trajectory. This comparison indicated that the break occurred near the muzzle, and metallic contact is maintained.

A Single Ring Brush.

The possibility of utilizing a single ring brush according to the plan conceived seemed now established. This plan involved making the gun itself one terminal of the chronograph circuit, thus utilizing the connection between projectile and gun as one of the brushes. From the projectile the current passed along a wire, imbedded in the wooden rod and connected with all of the copper bands, to the single brush at the muzzle which formed

the other terminal of the chronograph. As a single brush could now be used, the advantages of one in the form of a ring entirely encircling the rod were at once apparent, for, no matter which way the centripetal force urges the rod, a good contact with the ring is always assured, and, furthermore, the same ring may serve as a guide for the rod in its passage out of the bore.

The Accurate Cylindrical Rod.

Attention was next directed toward obtaining a perfectly true round rod. The necessity of this requirement may not appear so serious at first thought, but keeping in mind the high velocity of the moving rod, the case may be likened with advantage to that of a railroad train moving at the rate of a mile a minute upon a poorly ballasted track, compared with the smooth gliding of a train at the same speed on a good road-bed. The question of the most suitable material for a rod was considered. The great mass of a metal rod of suitable size and length, and the difficulty of preparing insulating bands upon it, pointed to the use of wood as the preferable material, and finally a fine piece of light white pine was chosen as the kind of wood to be used. The great length of this rod, which was only $1\frac{5}{8}$ inches in diameter, made it impossible to turn it when supported in the lathe by its extremities alone. An attempt to place a third support in the center caused much annoyance by chattering when run at a sufficiently high speed. Finally, a special tool was made which would support the rod and at the same time cut it to a true cylindrical shape. An iron collar with a hole just equal to the diameter of the desired rod was supported from the tool rest, and a specially made knife screwed upon this collar with its cutting edge turned so as to cut the wood in front of the collar as it advanced, down to a size which would just fit the hole. As the tool advanced the rod was polished by the friction in this collar, which left a perfectly smooth and accurately finished rod. Notches were then cut at the desired intervals to accommodate

the copper bands, which must be flush with the surface of the rod, by simply lowering the knife and running the tool in the opposite direction along the rod. This was done so that the tool would never come upon a smaller portion of the rod, since it served for a support.

Copper Conductors added to the Rod.

When the rod was turned a groove was cut along its entire length to accommodate a copper wire to be buried in it. Thin copper strips $\frac{1}{32}$ inch thick were cut to the desired lengths, and each made just long enough to completely encircle the rod without overlapping. These strips were first rounded between rollers, then wrapped around the rod and drawn very tight and close by winding a leather strap around it and drawing taut. Each edge was then secured by driving small brads closely along its length near the seam. The imbedded wire was next soldered to each strip of copper to secure good contact. Between the copper bands, in addition to the wire being sunk beneath the surface of the wood, further guard against metallic contact with the brush as it passed through was afforded by filling the groove flush to the surface with sealing wax. The rod was next replaced in the lathe and polished to an accurate, smooth surface. A view of the rod prepared for use is shown in Fig. 31. The shrapnel was bored out from the front to the base part with an inch drill to compensate for the additional mass of the rod, and a wooden plug driven in to give a firm bearing surface for the base of the ballistic rod. A collar was turned upon the nose of the shrapnel to receive the ballistic rod, which was firmly screwed in position. The wire imbedded in the rod was securely fastened to the projectile. At first this contact was secured by simply screwing down the rod, thus pressing the wire upon the shoulder. Later, when the supply of unloaded shrapnel was exhausted, and it became necessary to use common shell, this method of securing contact was no longer reliable, as there were no screw

threads in the projectile. It was more labor to prepare one of these common shell, as the front portion had to be cut off to make a bearing shoulder, and a hole bored through to the central cavity to admit the wire. Advantage was taken of the base percussion fuse to ensure good electrical connection. The fulminate and plunger were removed and the cavity filled with mercury, into which the wire passed through the perforation in the vent originally intended to admit the flame to the cavity. This arrangement of mercury cup contact, thus found already made, was as good as though especially designed for the purpose. After each rod and projectile were prepared they were carefully tested for good electrical contacts, since experience proved that contacts supposed to be perfect were sometimes defective, and neglect of this precaution would have lost much time.

Spacing of the Copper Strips.

By any "dynamical method" the observations give points along a space time curve. Since the number of these points is necessarily limited, their value greatly depends upon their position along the curve. The ideal positions of these points would seem to be at regular intervals along the arc of the curve itself. The form of the space time curve is known to be such that observations at equal time intervals more nearly conform to the ideal than at equal space intervals. This also has the practical advantage of using the chronograph itself under the most favorable conditions. The copper bands should therefore be of varying lengths, the shortest being at the point of the rod. Accordingly, for a first trial these lengths were approximated in a rough way by simply taking the space time curve to be a parabola, and the nearness of the approximation may be seen by the location of the observed points on the space time diagrams given with each shot. Each negative was examined before the intervals on the rod for the succeeding shot were determined. Naturally the first attempts had only a few long intervals along

the rod, and these were made shorter and shorter in succeeding shots to determine how near together the records might be easily obtained. Besides this, another idea kept in view in designing rods was to cause the observations of succeeding shots to fall intermediately between those of previous shots, so that the number of points would be greatly increased along a resultant curve reduced from all the shots. The intervals along the prepared rods were carefully measured with a steel millimeter tape, estimating to tenths of a millimeter.

The "Spider Ring Brush."

A single ring brush being possible, a new device for supporting it at the muzzle was constructed. A view of this device is shown in Fig. 32. *AA* is the wooden collar turned to fit the front of the chase, and prevented from displacement forward during discharge by the swell of the muzzle of the gun. *BB* are circular iron straps capable of adjustment, for securely holding the collar in position. The wooden collar was slit into four equal sectors, and the hard steel pieces *CC*, *DD*, extending the length of the collar, were securely screwed, one to each sector, to facilitate taking apart and assembling the support. The entire collar and steel strips were insulated from the gun by the insulating wood of the collar itself, and by wrapping tough paper upon the gun and assembling the collar over it. *EE*, *FF* are four other iron strips bolted to the former pieces as shown, and capable of adjustment along radii by means of slots for the securing bolts. These radial pieces served as immediate supports for the ring brush, which was grasped by four half circular holes in the inner edges of the radial strips. The form of the brush first used was an iron ring slightly larger than the rod, but experience finally led to the "spider ring brush," shown in the figure. This is made of $\frac{1}{4}$ inch brass rod bent into a circle of $1\frac{3}{4}$ inches internal diameter. Into this ring were driven spring brass wires $\frac{1}{20}$ inch in diameter, projecting

¼ inch in front of the ring and inclined at an angle inwards so as to press against the rod. These spring wires were added to insure a continuous connection with the rod, and cause the breaks in passing from copper to wood to be uniform and definite for each of the strips, since some of the spring wires are in contact at all times. One of the greatest advantages of this ring brush with its four radial supports is that it offers a very small surface to the action of the blast. A front view of the muzzle device with simple ring brush is shown in Fig. 33.

Pieces of the Rod Recovered.

It was naturally a point of great interest to know exactly how the rod behaved in passing out through the ring, independent of the chronograph record, which never gave a complete record throughout the whole length of the bore. The gun was pointed out to sea, and at the instant of firing nothing unusual could be observed, but an instant later the front part of the rod could be seen floating in the water about 500 yards distant. This part of the rod was recovered after each shot. The rods thus obtained were all of about the same length, and the fractured end showed in each case a similar cross break. The scratches along the copper strips made by the small spring wires of the ring brush were clearly visible, and also showed the rotational effect due to the rifling. Complete contact across each copper strip by some one of the spring wires of the brush could be traced. This corresponded to the record of the chronograph, and the break in the rod limited the extent of the observations to about 80 cms. along the rod, which corresponds to the first 80 cms., or about 2.62 feet, of the travel of the projectile. None of these pieces recovered showed any increase of blackening from the blast, but they certainly would have done so if such had been the case, for the polished surface of the copper was very susceptible to discoloration when even temporarily placed in a gun recently fired and ordinarily cleaned.

Though the break in the wood prevented records being obtained throughout the entire length of the bore, yet the points obtained thus far by this method extend about half the travel of the projectile. Fortunately, observations in the first half of the travel are most desired, as here occurs the point of maximum pressure and the greatest variations of all kinds. Moreover, this part of the curve needs more study than the other part, since the errors of observation are greater, and a less number of accurate experiments are known for this portion.

The ground immediately in front of the gun was carefully examined after each shot, and narrow furrows along the trajectory cut in the turf were often discovered. Besides this, small splinters of the rod and portions of copper strips were picked up.

Brass bolts were employed to fasten the radial strips (*EE* and *FF*, Fig. 32) which support the ring brush to the longitudinal steel strips, so that, by the shearing of these brass bolts as the projectile passed out, the ring and radial strips alone were carried away at each shot. This greatly reduced the labor in the preparation of each shot, for the entire muzzle collar and steel strips were unharmed, and were used throughout the experiments. The only parts of the muzzle apparatus destroyed with each shot were the ring, the four iron radial strips, and the brass bolts, and these could be prepared in quantity and ready for use. Since in these experiments it was necessary to examine the previous shot before deciding upon the spacing of the copper strips for the next shot, this delayed the workman somewhat: however, as it was, with a single mechanic, working an ordinary day, a speed of one shot per day was attained for two successive weeks.

The gun was uniformly fired at a quadrant elevation of 3°, and the muzzle preponderance caused by the weight of the chase-collar and brushes was counterbalanced by wrapping the prolonge over the breech and underneath the trail, thus preventing the depression of the muzzle and insuring the given elevation.

Remarks on Observations.

It is an advantage to have observations given in a graphical as well as tabular form, and accordingly they are presented by points indicated by crosses through which broken dotted lines are drawn. The importance of the graphical method of viewing problems of this character, exhibiting to the eye the fundamental relations which connect the different equations together, and making it possible to pass from one curve, which is the geometrical equivalent of an equation, to another in cases where the equations may be either unknown or very complicated, so that the equivalent process of algebraic elimination is impracticable, it seems has not been sufficiently emphasized, and for this reason it is thought the elementary character of the following explanations will be acceptable:

Without any special reference to ballistics, let us consider the abstract problem of the motion of a point along any line in space. Referring to Fig. 34, let the position of this moving point at any time be represented by the curve ABC. Time t is measured along the horizontal and the distance s from the origin along the vertical axis. Thus a point C upon the curve means

[redacted]

second, when it comes to rest, and then reverses its direction, arriving at the origin again after one second. The motion is then in the opposite or negative direction from the origin, and so continues till it comes again to rest after 1.577 seconds. It then returns to the origin and arrives there again after two seconds, and thereafter continues to depart from the origin in the positive direction. This is known as the space time curve. The velocity with which the point moves is algebraically represented by the first derivative of s with respect to t.

$$\frac{ds}{dt} = v = 3t^2 - 6t + 2. \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

But graphically the derivative is represented by the tangent of the angle which a line drawn tangent to the space time curve at any point makes with the time axis. Such a tangent is drawn at B, and its value is seen to be $+2$.* At this point an ordinate is drawn equal to $+2$, and this gives one point on the velocity time curve, as the point D. Any number of points could be similarly found and a continuous curve drawn through them. This curve thus graphically determined is the same as a curve representing equation (2), and in this case is seen to be a parabola. To interpret curve II physically, beginning with the point E, it is seen that the velocity of the point just starting from the origin is equal to 2 and in a positive direction, and by moving along the curve it is evident that the velocity is decreasing. At the point N where the curve crosses the axis the velocity is zero and the point at rest after 0.423 second, which was also evident from curve I. The velocity then becomes negative and reaches a maximum negative value after one second, and this occurs when the point, as seen by curve I, has

* Because of the different units used on the horizontal and vertical axes, the real angle is not the same as it would be when drawn to equal scales; but the tangent of the real angle is always found by taking the ratio of the sides of a triangle, measuring the vertical side by the vertical scale and the horizontal by the horizontal scale.

returned to the origin. In this way many features are readily detected by the eye which would not appear evident at a glance from the equation.

The acceleration which the point has is algebraically expressed by the second derivative of s with respect to the time, which is

$$\frac{d^2s}{dt^2} = a = 6t - 6. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This second derivative is also represented by a curve which may be derived graphically from curve II, as II was from I. When this is constructed, the points will lie upon the straight line III, which crosses the t axis at a point directly above the lowest point of the parabola, where $t = 1$, since here at the minimum point the tangent is zero and the velocity is not changing. Equation (3) when traced coincides with this line, which represents the acceleration time curve, and indicates that the law of motion of the point is a uniformly increasing acceleration.

The more desirable relations required in interior ballistics are those between velocity and space, and between acceleration (or pressure) and space, so as to know what the velocity or pressure is at any point of the bore. These relations may be derived graphically from curves corresponding to I, II, and III, by a process to be described. This may sometimes be done algebraically, but the process involved consists in eliminating one variable between two equations, which in general is not a simple problem. If the variable t is eliminated between equations I and II, the desired velocity space equation will be obtained, and the result seen to be a higher degree equation. The graphical solution of this, however, is simple, and represented in Fig. 34 by curve IV. To obtain this make use of curves I and II. To obtain any point as M on the new curve, measure the ordinates of curves I and II, corresponding to the abscissa OH, and take HK as the abscissa, and HG as the ordinate of the new point. This locates the point M on the new curve, and a similar con-

struction gives any point on the velocity space curve. By eliminating t between equations (1) and (3) the acceleration space curve is obtained, or graphically by a similar construction as before between curves I and III, the points of curve V are obtained, which is the required acceleration space curve.

Data.

The data obtained from each shot prepared to give a record of interior ballistics, together with that from the chronographic negatives, are given below, and no attempt is made to derive an equation to represent the velocity and acceleration or pressure throughout the bore, except in cases where five or more points are obtained on the space time curve.

The powder used throughout these experiments was I. K. H. Dupont Powder, 1891, lot 27, 3.2-inch breech loading rifle. Specific gravity 1.725. Volume of chamber with shrapnel 111.367 cu. in. The density of loading with shrapnel is .95713, and the reduced length of initial air space 0.5022 ft. Volume of chamber with shell 104.55 cu. in. This difference in volume of chamber with shrapnel and shell is due to the difference in the position of the band.

Shot I.

August 7, 1895.

Weight of projectile,	12 lbs. 4 oz.
Weight of rod,	1 lb. 14 oz.
Total,	14 lbs. 2 oz.
Weight of charge (with sack),	3 lbs. 14 oz.

This shot is the one previously described, using the method represented in Fig. 30.

The distances s are measured along the rod from the inner side of the copper band nearest the muzzle, which was in each

case so adjusted that the first movement of the projectile from its seat would break the chronograph circuit. This is evidently the zero point from which to measure the travel of the projectile. The angles θ are measured upon the negatives from that break of the chronograph record which corresponds to the first motion of the projectile just mentioned. The corresponding time is obtained from θ by the relation $t = \frac{\theta}{\omega}$ which holds for uniform rotation where ω represents the angular velocity of the plate. The angular velocity ω is obtained from the tuning fork record by measuring the angle subtended by any convenient number of complete waves. The angle subtended by 22 waves in this case is 216.285 degrees, and the time corresponding to one complete wave of the fork used is known to be $\frac{1}{256}$ of a second. This determines the angular velocity, which is $\omega =$ 2516.8 degrees per second.

No.	s (cms.)	θ (degrees)	t (seconds)
1	35.6	11.067	.00440

Shot II.

August 14, 1895.

The first shot with the chronograph circuit through the projectile and gun.

Weight of projectile,	11 lbs.	13 oz.
Weight of rod,	3 lbs.	10 oz.
Total,	15 lbs.	7 oz.
Weight of charge,	3 lbs.	13½ oz.

278.692 degrees of tuning fork record correspond to 27 waves. Hence

$$\omega = 2642.4 \text{ degrees per second.}$$

No.	s (cms.)	θ (degrees)	t (seconds)
1	19.1	9.271	.00351
2	76.25	17.900	.00677

Shot III.

August 19, 1895.

First trial with the "spider ring brush."

A turning fork of higher pitch was first used for this shot, and continued to be used for all remaining shots. Its frequency was 511.601 complete vibrations per second.

Weight of projectile,	11 lbs.	13 oz.
Weight of rod,	3 lbs.	5 oz.
Total,	15 lbs.	2 oz.
Weight of charge,	3 lbs.	13 oz.

185.372 degrees of tuning fork record correspond to 23 waves. Hence

$$\omega = 4123.4 \text{ degrees per second.}$$

No.	s (cms.)	θ (degrees)	t (seconds)
1	5.75	6.114	.00148
2	22.92	12.528	.00304
3	52.20	18.792	.00456

Shot IV.

August 21, 1895.

Weight of projectile with rod,	15 lbs.	5 oz.
Weight of charge,	3 lbs.	$13\frac{1}{2}$ oz.

214.922 degrees of the tuning fork record correspond to 28 waves. Hence

$$\omega = 3927 \text{ degrees per second.}$$

No.	s(cms.)	θ (degrees)	t (seconds)
1	5.78	5.934	0.001511
2	22.92	14.583	0.003713
3	52.14	22.599	0.005755

Shot V.

August 23, 1895.

Weight of projectile with rod, 15 lbs. 2½ oz.
Weight of charge, 3 lbs. 13½ oz.

$\omega = 5933$ degrees per second.

No.	s (cms.)	θ (degrees)	t (seconds)
1	3.81	5.433	.000916
2	10.19	10.744	.001811
3	19.09	16.079	.002710
4	31.14	21.114	.003559
5	48.94	26.011	.004384
6	71.80	31.917	.005380

Shot VI.

August 24, 1895.

Weight of projectile,	11 lbs.	12 oz.
Weight of rod,	3 lbs.	1 oz.
Total,	14 lbs.	13 oz.
Weight of charge,	3 lbs.	10¼ oz.

$\omega = 6131$ degrees per second.

No.	s (cms.)	θ (degrees)	t (seconds)
1	3.85	5.278	.000861
2	9.60	9.439	.001540
3	17.80	13.386	.002183
4	28.00	17.994	.002935
5	40.77	22.798	.003719
6	57.30	27.717	.004521

Shot VII.

August 26, 1895.

The unloaded shrapnel on hand had been exhausted, and common shell was used first with this shot, and with all following ones.

Weight of projectile with rod, 15 lbs. 7 oz.
Weight of charge, 3 lbs. 13½ oz.

267.075 degrees of the tuning fork record correspond to 23 waves. Hence

$$\omega = 5940.8 \text{ degrees per second.}$$

No.	s (cms.)	θ (degrees)	t (seconds)
1	3.81	4.472	.000753
2	9.60	9.366	.001577
3	17.86	14.105	.002374
4	27.90	17.955	.003022
5	40.66	21.952	.003695
6	57.15	26.239	.004417

Shot VIII.

August 27, 1895.

Weight of projectile, 11 lbs. 13½ oz.
Weight of rod and mercury, 3 lbs. 13 oz.
Total, 15 lbs. 10½ oz.

A mercury cup connection was first used with this shot, as previously explained.

Weight of charge, 3 lbs. 13½ oz.

$$\omega = 5883.4 \text{ degrees per second.}$$

No.	s (cms.)	θ (degrees)	t (seconds)
1	3.40	4.222	.000718
2	8.90	7.392	.001256
3	16.40	10.903	.001853
4	26.35	15.031	.002555
5	39.40	19.261	.003274

Shot IX.

September 3, 1895.

Weight of projectile,	11 lbs.	14½ oz.
Weight of rod,	3 lbs.	4 oz.
Total,	15 lbs.	2½ oz.
Weight of charge,	3 lbs.	13½ oz.

$$\omega = 5514.8 \text{ degrees per second.}$$

No.	s (cms.)	θ (degrees)	t (seconds)	mean error of t
1	5.8	5.499	.000997	.0000196
2	13.85	10.341	.001875	.0000316
3	23.86	13.746	.002493	.0000285
4	35.85	17.794	.003227	.0000277
5	49.82	21.553	.003908	.0000187
6	65.80	25.548	.004633	.0000232

The muzzle velocity was found for a weighted projectile by means of three exterior screens, and the crusher pressure gauge was also used.

September 2, 1895.

Weight of projectile,	15 lbs.	14 oz.
Weight of powder,	3 lbs.	12¼ oz.
Weight of sack,		1¼ oz.

213.66 degrees of the tuning fork record correspond to 22 waves. Hence

$$\omega = 4968.6 \text{ degrees per second.}$$

The distance from the muzzle to the various screens prepared is denoted by s.

No.	s (feet)	θ (degrees)
1	19.77	0.000
2	29.80	32.334
3	40.13	65.638

The first break in the chronograph record occurred at the first screen 19.77 feet from the muzzle. The velocity calculated from the interval between the 19.77 and the 29.80 points is 1541.2 ft. per second. That calculated from the 29.80 and 40.13 interval gives 1541.1 ft. These velocities expressed in meters per second are 469.73 and 469.77. If the former experiments in determining exterior velocities are taken as a guide, some of this observed velocity at a distance of twenty feet should be deducted to obtain the true muzzle velocity. From previous measurements it is not too much to say that the muzzle velocity is thirty or forty feet less than the observed value, which would bring it down to about 1500 ft. per second or 457 meters per second. It will be remembered that the corresponding velocity for service conditions when the shell is not weighted measures in the neighborhood of 1650 feet per second, and is thus about a hundred feet per second greater than the velocity just given.

The crusher gauge registered a pressure of 34,000 pounds per square inch.

The measurements given for shots 1, 2, 3, and 4 are represented graphically in Fig. 35, and for shots 5, 6, 7, 8, and 9 in Fig. 36. The points represented by crosses are observed points, and those belonging to a single shot are connected by broken lines. It will be noticed that the observed points only extend through the first 72 cms. of the bore, which is itself (measuring from the base of projectile in its seat to the muzzle) 184.4 cms. long, and thus the observations extend through almost half the travel of the projectile. In this distance the greatest number of points observed is seven, and these are all recorded in $\frac{5}{1000}$ of

Remarks on Observations.

ıdvantage to have observations given in a graphical ıabular form, and accordingly they are presented by licated by crosses through which broken dotted lines The importance of the graphical method of viewing ns of this character, exhibiting to the eye the fundamental ions which connect the different equations together, and it possible to pass from on urve, which is the geomet- valent of an equa nother in cases where the may be either u very complicated, so that ılent process of algebr imination is impracticable, as not been sufficiently em ıasized, and for this reason ught the elementary chara of the following explana- ns v be acceptable:

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$$s = t^3 - 3t^2 + 2t, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which s is the distance from the origin of motion in meters, and t the time.

Curve I is a representation to scale of this equation, and does not in any way represent the real path of the point in space, which may be along a line of any kind, but it is simply a scheme to show how far the point is from the origin at any time. To interpret this particular curve it is seen that the point starts at the origin and moves in the plus direction for 0.423 of a

other and more complicated formulæ than that of a parabola, which are usually advocated.

The equation of the velocity time curve, found by differentiating the former equation with respect to t, is $v = 56{,}600t$, where v is expressed in meters per second, and t in seconds. The velocity space curve found by eliminating t between the two equations given is $v^2 = 11.32s - 24$, and is also a parabola. The acceleration time equation is found by differentiating the velocity with respect to t, and is $a = 5{,}660{,}000$ cms. per second, which is 5740 times the acceleration of gravitation, and is constant. Since acceleration is directly proportional to the pressure on the projectile (neglecting friction) it follows that the pressure over the distance where the parabola coincides with the observations is approximately constant. It must not be inferred from this statement that the parabolic law involving constant pressure, found to be so approximately true through a certain range of the travel, obtains for portions of the bore either in rear of or in advance of this region. In fact, it is well established, especially for quick burning powders, that the pressure sensibly decreases along the chase. As to the very first motion of the projectile which caused the first signal on the chronograph, it is seen from this and succeeding figures that the first point invariably lies below the parabola, and usually considerably off from it as compared with the others. This of itself indicates that there is considerable departure from the parabolic form, and it seems to be confined to the first few (about five) centimeters from the origin, corresponding to about $\frac{1}{1000}$ of a second. In other words, for the powder used and the conditions of loading employed, the point of maximum pressure seems to be located within this region. In any case this is the region of greatest changes of all kinds, and although most important to know as far as gun construction is concerned, yet it is the most difficult to measure. It seems clearly settled, however, that this maximum point, under the above named conditions, lies nearer to the origin than has heretofore been supposed. We have only succeeded

thus far in obtaining a single point that seems to lie within this region of maximum pressure, which is manifestly far from being sufficient to determine the exact position of it; but if slower burning powder had been used it looks quite probable that the maximum point might be approximately located.

The pressure which corresponds to the constant acceleration of 5,660,000 cms. per second, or 5740 g., is found to be about 11,100 pounds per square inch on the base of the projectile, which weighed 15 pounds 7 ounces. This value, which is the probable pressure along the part of the bore where the parabola applies, it will be seen might have been much greater near the seat of the projectile without making very much change in the space time or velocity space curves. To illustrate this point some dotted curves are drawn in Fig. 13, which figure represents the data from shot No. 9. The parabola in this case representing the space time curve has its origin to the left of the vertical axis instead of upon it, as in the previous case. The true space time curve must manifestly pass through the origin as the time is counted from the instant when the projectile started. It apparently blends with the parabola in a very short time. The dotted curve from the origin represents a possible position of the true curve which soon blends with the parabola. Now, assuming that this is the true curve, the other curves may be graphically found. The points on the velocity time curve II are obtained by erecting ordinates equal to the tangent of inclination to the space time curve I. It is evident also that the velocity time curve must pass through the origin, since the velocity is zero when the time is zero. This shows that curve I should be tangent to the horizontal axis at the origin. As the curves are drawn there is a point of inflection in the velocity time curve at A, and a tangent line is drawn at this point. It will be remembered that the pressure on the base of the projectile is proportional to the tangent of the angle which the tangent line drawn at any point of this curve makes with the horizontal. This point would therefore correspond to the point of maximum

pressure, as the tangent has here its greatest value. This particular inclination is chosen because it corresponds to a pressure of 34,000 pounds per square inch, which is the registered pressure of the crusher gauge. It is noticeable here how a small change in the inclination of this line will make a great change in the pressure. This great pressure may have actually existed for a very short time near the beginning of the travel, but it looks somewhat doubtful that such a large value did exist.

In connection with this subject we cannot omit to mention that theoretically the pressure *recorded* by a crusher gauge when the pressure is *suddenly* applied (and this means instantaneously) is just twice as much as that which would be recorded by the same pressure slowly applied, as it is when the copper cylinders are tested. Now the fact that the maximum point seems located so near the origin, meaning that the pressure is very suddenly applied, would perhaps cause the crusher gauge to register more nearly the theoretical limit of double pressure than that which the testing-machine gives. At any rate it would be somewhere between these two limits, as the pressure is surely not slowly applied, and, not having any experiments to show which limit is actually nearer to the truth, it must be entirely a matter of judgment to decide this question. According to this statement, the true maximum pressure lies somewhere between 34,000 and 17,000 pounds per square inch, as indicated by the crusher gauge, and it remains to the judgment to decide which is the nearer limit. The value which certainly exists further along the bore in the region we have measured is less than the smaller limit.

It is naturally of interest to see what muzzle velocity the parabolic law gives, assuming it to hold for regions of the bore in front of the observations. The travel of the projectile using common shell, meaning the distance from the base of the projectile in its seat to the muzzle, was measured to be 184.4 cms. In the case of shot No. 7 the equation for the velocity-space curve is $v^2 = 11.32s - 24$. Substituting the muzzle distance for s, we have $v = 446.2$ meters per second. In case of shot

No. 9 the corresponding computed velocity is 423 meters, and for shot No. 5 it is 421 meters.

It was impracticable to measure the muzzle velocity with each shot in the ordinary way by exterior screens, because of the ballistic rod which projected in front of the projectile. Accordingly a special experiment was made to determine this, using a weighted projectile, but inasmuch as the weights of the ballistic projectiles were not exactly uniform, only an average weight was used, and the muzzle velocity observed at 25 feet from the muzzle was found to be 469.7 meters.

The increase of velocity after the projectile leaves the muzzle was observed in former experiments to be as much as ten or twelve meters, and we would be justified in assuming that the true muzzle velocity is nearer 457 meters than 469.7. It is evident that there is much uncertainty as to the exact value of the true muzzle velocity, as under the same conditions of service charge the velocities were observed to vary considerably, from 557 to 585 meters per second. It appears that the calculated velocities are therefore fairly coincident with the probable muzzle velocity.

In a similar manner a parabola has been fitted to the observations in shot 5, and is represented in Fig. 39.

To obtain an idea of the appearance of a record for interior as compared with exterior ballistics, refer to Figs. 40 and 41 for interior and 42 for exterior. Fig. 40 is the record of shot No. 4, and 41 that of shot No. 9. The intervals between the screens for the exterior record were about ten feet.

Conclusion.

When the two objects of these experiments mentioned in the beginning of this paper are kept in view, namely, first, to improve the instrument, and second, to obtain measurements of the motion of projectiles through the bore without mutilating the gun in any way, it may be said that the two vital parts of

the instrument have each been improved. These parts are the chronograph and tuning fork records, upon which the measurements are made. The intensity of the light for the chronograph record has been increased as described by the use of lenses, so that it is even more quick in its response to breaks in the electric current than formerly. This becomes a more important matter where the measurement is upon projectiles inside the bore than it was for exterior ballistics, because the time intervals to be measured are generally much shorter in the former case.

The improvements in the tuning fork records are more noticeable in the photographs than those in the chronograph records. The photographs, examples of which are shown in Figs. 27, 28, and 29, are easily obtained, and have the wave lengths so clearly defined that there is little to be desired in point of accuracy. These records are interesting from a purely physical point of view, and when it is understood how easily they may be obtained, it seems certain they must find a place in laboratory investigations where former methods left so much uncertainty as to the exact location of the maximum points of the waves.

Naturally many radical changes in the camera formerly used were suggested, such as the employment of sensitized films wrapped upon a cylinder instead of a plane glass plate; and such as a form of instrument in which the plate is stationary while the beam of light revolves. The process of developing and subsequently drying a film is too liable to cause change of shape, which renders its use wholly unsuited for such accurate measurements as are involved. The first instrument required the sensitive plate to be mounted like a circular saw upon its shaft, requiring a hole in the negative itself. The new instrument will permit the use of ordinary commercial plates mounted in plate holders so that the plate and holder revolve together. Allowance is made for the varying thickness of the glass, and consequent eccentricity of the centre of gravity by mounting the whole in a comparatively heavy well balanced fly wheel.

It should be said that the original camera is the only one

which has as yet been used in the experiments already described. A new instrument is now almost completed, being manufactured by the well known optician and instrument maker, J. A. Brashear of Allegheny, Pa., U. S. A. A special form of instrument to accompany the chronograph for the purpose of accurately measuring the angles obtained on the negatives is in the hands of Messrs. Warner & Swasey of Cleveland, Ohio, U. S. A., the well known makers of astronomical instruments. It is expected that these instruments will be installed at the U. S. Artillery School, Fort Monroe, Va., and be ready for use in a few months.

As to the second object mentioned above, it may be said that as many as seven observations of the projectile were taken in a distance of 57 cms. (only 1 foot 10½ inches)—somewhat less than one third the whole travel of the projectile, which is 184.4 cms. The shortest distance between observations was 3.8 cms. (about 1½ inch). The greatest distance observed along the bore was about 76 cms. (2½ feet). No attempt was made to remove what is thought to be the cause of the breaking of the rod, and with it the limitation to the distance measured along the bore, on account of lack of time to do more than obtain the results mentioned. It is thought, however, that these observations can be extended still further along the bore than they have as yet been observed.

An important point to be kept in mind is that the method used permitted a single mechanic working all day to prepare all the material used for a single round, so that for more than a week consecutively one shot was fired per day. This, moreover, was under experimental conditions, which obviously required more time than it would to do the same thing under other conditions; for example, the distances on the rod between the copper bands of the succeeding shot were not determined until the preceding shot had been fired and the negative examined. It would be perfectly feasible to keep these rods already prepared for the special use of taking interior velocities. In that

case the operation of observing a projectile inside the bore is almost as easily performed as observing it outside.

Although what has been said in this paper applies more particularly to the experiments with a 3.2-inch field rifle, it is not to be inferred in consequence that there is no application to guns of larger caliber. On the contrary, there is much reason to believe that experiments upon big guns, though the preparation for each shot may require a larger plant and take more time, will be even more successful than with a 3.2-inch rifle. The first part of the travel is unquestionably an important one to know something about, and, for an equal distance in the two guns, the velocity of the projectile may be much slower in the big gun. Even though the observations could not be extended throughout the entire bore, it would be a particular advantage to measure the first part of the motion.

THE NEW POLARIZING PHOTO-CHRONOGRAPH AT THE U. S. ARTILLERY SCHOOL, FORT MONROE, VA., AND SOME EXPERIMENTS WITH IT.

It was stated at the close of the previous paper that the Polarizing Photo-chronograph authorized by the Board of Ordnance and Fortification, U. S. A., for the U. S. Artillery School, was then nearly completed.

The object of this paper is to describe this instrument and its installation, together with some of the further tests and experiments with it which were carried out in the electrical laboratory of the school, where the new instrument was installed during the months of July and August, 1896. It is a pleasure to record at the outset our obligations to Mr. J. A. Brashear of Allegheny, Pa., who constructed the chronograph, and to Messrs. Warner & Swasey of Cleveland, Ohio, who constructed the measuring instrument for the same.

The well known reputation of each of these firms in their particular lines of work has more than been sustained, and their skill in execution, as well as their experience in methods, has contributed no small share in making the instrument what it is at present.

In arriving at the general form which the new instrument has assumed, naturally many radical departures from the form

with which the first experiments were conducted were considered, and constructions of the camera which would permit of greater possible length of record, such as wrapping a sensitive film upon a cylinder or by causing the record to assume a spiral form upon a plane sensitive plate, which would suggest themselves almost immediately, were discarded as introducing complications of construction unnecessary for the particular object for which this form of instrument was intended, and the advantages of the general form of a movable plane glass sensitive plate appear more and more apparent with increase of experience.

Since the primary object of this apparatus is the accurate measurement of very minute intervals of time, its particular sphere of merit is in the quantitative investigation of natural phenomena beyond the reach of other methods of measurement, and where the whole period within which measurements are sought is *itself* a small interval of time when compared with a second, for instance.

For this reason, great length of available record, which means roughly comparatively long intervals of time, is unnecessary for the very rapid phenomena which are usually met with in scientific gunnery.

Description of Chronograph.

The essential features of the chronograph, as explained in the first paper, to which reference is made, are the transmitter and the receiver. The former consists naturally of a series of lenses and prisms in the same line with the arc light and tube, so that it makes the apparatus long as compared with the width. In fact it is made like an optical bench, a very convenient form being the inverted T rail shown at O and O', Figs. 43, 44, and 45. Fig. 43 shows the general arrangement of the parts of the apparatus in plan and elevation. Figs. 44 and 45 are views of the

instrument in which the lettering corresponds to that of Fig. 43. Upon the rail O' are first the arc lamp a, one of J. B. Colt's lamps, and in front of it the condensing lens L. The polarizer P is between the lens L and tube T, and immediately after the tube is the analyzer A and lens L'. The receiver has the form of a sensitized glass plate revolving in its plate holder, which is itself mounted in a heavy cast iron fly wheel W. Both receiver and transmitter are assembled upon the same cast iron base plate, which is 7 feet 3½ inches long by 2 feet wide. The second T rail seen at O carries the accessories for the tuning-fork, which makes its record upon the sensitive plate on the opposite side to that where the chronograph record appears. Inasmuch as uniform velocity is always used in taking records, it can make no difference where the tuning fork record is placed. This rail O carries first a mirror, M, which reflects the light from the arc and turns it in a line parallel with the rail. It then passes through a large condensing lens L'', and an image of the arc is formed upon a small piece of aluminium foil attached to one prong of the tuning fork F. This foil has a small round hole in it about one mm. in diameter, which is brightly illuminated by the light. The lens L''' forms a magni-fied image of this luminous hole upon the moving photographic

$1\frac{1}{8}$ inches in diameter, carried by the ball bearings at BB. The detail of this shaft and its bearings is shown in Fig. 46.

The armature of a $\frac{1}{8}$-horse power electric motor m, manufactured by the Crocker-Wheeler Co., is directly coupled to the camera shaft. The motor is not specially constructed, but is one of their standard commercial types. The wheel is so nicely balanced that it will rest in any position where it is left, but the slightest touch of the hand is sufficient to turn it. The motor is wound for low voltage, about twelve volts being the highest ever needed. The inertia of the wheel is so great that it takes several minutes to attain full speed, and it will run many minutes after the power is cut off before coming to rest.

In describing the camera itself reference is made to the detail drawings Figs. 47, 48, and 49. A vertical section through camera, wheel, and shaft is seen in Fig. 48. The front elevation of the dark chamber is represented in Fig. 47, and through the camera wheel in Fig. 49. The plate holder is made of metal to accommodate two plates 12×12 inches square, and slides through the opening O in the wheel (Figs. 48 and 49), upon the track SS (Fig. 49). The holder is held in position by four thumb-screws, $CCCC$ (Fig. 44) to prevent the possibility of its flying out when rapidly rotating.

The front part of the camera, shown in elevation Fig. 47, is a casting D, bolted to the base plate, and in the form of a ring with a section of such a shape that it surrounds the rotating wheel so as to prevent any light from reaching the sensitive plate when the slide is drawn from the plate holder. The wheel W has a flange upon the circumference of it, the section of which just fits the stationary ring D, making a small clearance, and after the solid cast ring D is bolted down the light brass ring R is screwed on so as to serve as additional security against outside light. This arrangement has proved to be entirely effectual in preventing fogging of the plates.

The light for the chronograph record is made to pass through a narrow radial slit, and to produce as sharp and definite records

as possible, it is desirable to have the slit close to the sensitive plate itself. To support the slit in this position a thin brass plate E, Fig. 48, is screwed to the back of the ring D, covering the whole of it, and thus forming a complete screen, preventing any light entering from in front. The detail of this brass partition is shown in Fig. 50. At G is the radial slit, having upper jaw J fixed and edge coinciding with a radius of the wheel. The lower jaw J' is pivoted at the center C, and may be clamped in any position by the thumb screw H. The upper edge of J' is also a radius of the wheel, and thus this arrangement always insures a radial slit capable of adjustment for any width.

Since the camera slide shutter must fall immediately in front of this slit in the brass partition to shut off all light before and after exposure, it makes it necessary to have no projecting parts on the front of the brass plate which would interfere with the shutter in its fall.

The light from the tuning fork reaches the plate through a round opening K. This hole is made in a small slide N, movable diagonally along a slot Q. The slot Q is made in a second slide U, movable vertically along the guides XX. This arrangement permits the adjustment of the hole K along a radius of the wheel, and neither interferes with the jaw J', pivoted at the center, nor has any projections which the camera slide might strike in falling. Across the hole K in the slide N are secured several fine vertical wires, the shadows of which form the centering circles upon the plate, as previously explained.

The Camera Slide Shutter.

In order to control the time of exposure of the slit so that the sensitive plate may not revolve more than once while the slit is open, a camera gravity slide shutter is provided. This shutter is shown in elevation in Fig. 5. It consists of a frame of thin sheet metal PP', forming a curtain with an adjustable rectangular opening at R.

When this shutter is raised the lower part P' normally covers both the radial slit and the opening for the tuning fork record, and is held suspended by an automatic catch upon the armature of a small electro magnet which is permanently attached to the inside of the ring D, with its binding-posts on the outside, and is not shown in the figure. To operate the shutter at any distance from the camera, it is only necessary to close an electric circuit passing to the binding-posts referred to. Since this shutter has considerable weight, its lower circular edge at T is provided with a thick rubber *cushion* extending along the entire lower edge, which serves to soften the shock of the fall. In order to prevent the possibility of the shutter rebounding sufficiently to expose the slit a second time, an automatic bevel catch lock is attached to the inside of the ring D at its lowest point. In rising and falling the shutter rides between vertical guides GG, Fig. 47, upon the four bevelled rollers *mmmm*.

The adjustable edge n of the shutter can be clamped by means of thumb screws, not shown, at any desired measured distance from the fixed edge o, graduated metal scales being marked upon the sides of the frame for the purpose of setting.

The operation of this shutter in opening and closing the radial slit is as follows: The shutter being up, its lower part P' closes the slit, and upon being released when it falls a certain fixed distance, the edge o first exposes the slit, and it remains exposed until the upper edge n closes it in the fall. The total time of exposure may by this means be set for any time ranging from zero to a certain maximum, about a tenth of a second.

To cover the entire front of the camera ring D a wooden circular face is provided, which can be removed at pleasure, and two small windows upon either side sliding longitudinally in grooves permit the light for the chronograph and tuning fork records to enter. This cover is simply an additional precaution, and to provide a means of exposing the slit by hand independent of the camera shutter when desired. This cover in position forms an additional small dark chamber in the space between the

camera shutter and the front face of the stationary camera ring *D*. In the ordinary use of the camera slide shutter for exposing the plate this wooden cover may be dispensed with.

The Gravity Switch.

The gravity switch and its function in exposing the camera and firing the gun has been explained in the first paper. The form for the new instrument is substantially the same as the rough one made for the first experiments. It is shown at *U*, Figs. 44 and 45; and, for convenience in setting and dropping the firing weight, the central rod along which the square brass cylinder falls is permanently graduated in inches, as also are the side rods which bear the pairs of binding-posts for the electric primer and the camera release electromagnet.

The Plate-holder.

The metal plate holder is inserted at the opening *O*, Fig. 48, in the periphery of the camera wheel *W*, and carries two ordinary commercial sensitive plates 12 by 12 inches, which are inserted and withdrawn in the ordinary way. Two thin metal slides are provided which can be withdrawn after the holder is inserted and before the camera wheel is started to revolve. To enable plates of smaller size to be used when desired, each side of the plate holder has a metal nest form which can be inserted, and takes an 8 by 10 plate.

Since the plate holder itself possesses considerable mass and is sometimes required to be revolved at high rates of speed, it is desirable to prevent any play between the glass plate and its holder. This is accomplished by tightening thumb screws in the holder which bear against the edge of each plate through the intervention of springs similar to those ordinarily employed in commercial plate holders. As already mentioned, the entire plate holder is firmly secured in position within the camera

wheel W by four screws $CCCC$, Fig. 44, which pass directly through the side frame of the holder itself.

Tubes and Coils.

The particular shape and size of the tube for the carbon bisulphide, and the constants of the coils to obtain the desired light upon the plate, depend upon the electromotive force which is employed in the transmitter circuit, and the resistance and inductance of the rest of the circuit including the line.

These conditions being determined, a tube coil can be wound which will be most effective. During the tests of the chronograph some account of which will follow, several tubes were made and used, but the one suitable for use in the ordinary case of taking velocities, and which was specially made with the chronograph, is shown at T, Figs. 44 and 45, and is wound of No. 18 cu. wire in four sections having an ohmic resistance in series of 12.7 ohms and in parallel of 0.84 of an ohm.

Inductance of four coils in series = 0.084 henrys.
Inductance of four coils in parallel = 0.0052 henrys.

The Nicol Prisms.

The size of the Nicol prism used as polarizer is 7.7 cms. long and 2.6 cms. in diameter. This is much larger than the one used as analyzer. The use of the condensing lens in front of the arc light makes it possible to use a much smaller analyzer, since the arc is brought to a focus at a short distance beyond it. The smaller analyzer also has the advantage of absorbing less light on account of its shorter length. The dimensions of the analyzer are 3.6 cms. long and 1.4 cms. in diameter.

Tuning Forks.

A set of eight standard forks were imported from Koenig, Paris, selected as being suitable to cover the range of speeds

which would ordinarily be employed for the sensitive plate in actual practice.

There are two each of 250, 500, 1000, and 2000 vibrations per second, one set to be used as standards with which to compare the others when they are used with the aluminium foil attached. The universal mounting for the different forks shown at F, Figs. 44 and 45, permits of an adjustment of the prongs of the fork for height and also transversely with respect to the optical T rail.

The lenses L'' and L''', Figs. 43, 44, and 45, besides being adjustable for height as are the other lenses, have also a transverse adjustment to facilitate placing the image of the luminous hole in the foil upon the fork at the exact position desired.

The Mounting of the Chronograph.

To provide a firm support for all the apparatus, a solid brick pier was built upon a concrete foundation placed beneath the floor of the laboratory, and finally the base-plate was set and levelled in suitable cement, and firmly anchored down by four bolts about 4 feet long extending from the four corners of the base plate down beneath the floor.

Process of Developing the Plates.

No simpler manipulations in the art of photography can be imagined than those required in the use of the chronograph. In the first place no prints are ever required, the measurement being made directly from the negatives themselves. Since there are no lights and shades to look out for as in taking ordinary views, where it is sometimes contrast which is desired and sometimes lack of contrast, the process of developing merely consists in pouring the liquid "developer" so as to flow the plate uniformly and quickly, and then rocking the tray until both tuning-fork and chronograph records show plainly. The plate is then

"fixed" in the ordinary way. Almost any developer may be employed, and there are many different kinds, some being two fluid and others one fluid developer. The two fluids are mixed just before developing. In practice the single fluid is more convenient, for it is ready at a moment's notice. Such a developer will keep for months if kept in glass stoppered bottles in the dark room. A formula which gives very satisfactory results is:

One Solution Developer.

Water, 100 parts or 10 ounces.
Metol, 1.5 parts or 75 grains.
Sulphite of soda cryst., 10 parts or 1 ounce.
Sodium carbonate cryst., 10 parts or 1 ounce.

Or substitute for sodium carbonate cryst.

Carbonate of potash, 5 parts or ½ ounce.

The metol to be dissolved in water *before* the addition of sulphite.

This may be diluted with water to suit the work in hand, the formula as given being very strong developer sufficient to cause an ordinary plate to flash up quickly.

Kind of Plates Used.

A rough calculation will show how very short is the time of exposure of any one point on the plate for the chronograph record. Supposing the width of slit to be 1 mm. at a distance of 150 mms. from the center of revolution, and that the plate rotates ten times per second, the whole distance travelled by one point on the plate per second is $10 \times 2\pi \times 150 = 3000\pi = 9424.8$ mms. The exposure is therefore .000106 second, for the point crosses the millimeter slit in this time. The desirability of having the most sensitive plates which can be made is clearly manifest. It is only the intensity of the light from the arc focused by the condensing lens upon the sensitive

plate which makes up for the shortness of the exposure. This instrument affords a convenient way of testing plates; for the conditions may be almost exactly repeated for different plates. The same speed gives the same kind of exposure. Some different plates were tried with a view of finding the quickest ones. No plates have been tried which equal the Stanley plate marked "sensitometer 50" for quickness. These have consequently been used exclusively for the experiments.

The Measuring Instrument for the Chronograph.

After the negatives have been obtained by means of the chronograph, in order to determine velocities of a projectile or other moving body, measurements are taken from the negatives. For this particular form of record an angle measuring instrument is required, and a form of instrument specially adapted to the purpose was designed.

A view of this instrument is shown in Fig. 51. The parts are assembled upon a cast iron base plate *A*, 24 by 27 inches, which rests upon three rubber legs, and although ordinarily upon a firm pier, it can if desired be easily moved and set upon a table for use at any part of the room. From the center of this base plate *A* is mounted the conical bearing upon which revolves the divided circle, the spokes of which are seen at *SSSS*, as well as the upper plane glass plate *B*, 42½ cms. in diameter and 9 mm. thick, upon which the negatives are mounted when measurements are to be taken. The weight of the glass plate upon the conical bearing is relieved and adjusted by means of a vertical spiral spring in the top of the conical bearing itself.

The plate *B* and the divided circle thus revolve together upon the conical bearing, and can be turned by means of the four arms with spherical mahogany handles shown at *HHHH*, clamped in position by means of the hand screw *J*, and given small motions by the tangent screw *K* with its spring cylinder *L*. By means of the hollow milled screws *N* and *N'* at right

angles to each other, and their corresponding spring cylinders O and O', the center of the large glass plate B has an adjustable motion in a horizontal plane with respect to the vertical axis of the instrument. This is accomplished by having the glass plate B mounted upon a second conical collar of considerably larger internal diameter than the external diameter of the main bearing cone, which collar slides horizontally on a plane surface with respect to the bearing cone, under the control of the screws and springs N and N' and O and O'. The object of this independent movement of the plate B with respect to the axis of the instrument is for the purpose of accurately centering the glass negative before readings are made.

The fine circle upon which the measurements are taken is made of silver, and divided by Messrs. Warner & Swasey's celebrated circular dividing engine. It has no graduation numbers marked upon it, and is protected from dust by the metal covering shown at M, which has its upper face graduated and numbered to read one-half degrees, and, together with a sliding pointer which moves with the glass plate, serves as a rough circle to read angles to half degrees, the finer readings being then taken from the silver circle beneath.

Bolted to the base plate are two uprights DD which support the cross piece E upon which the reading microscope F is mounted. This microscope has a motion of translation along a diameter of the glass plate by means of the rack e, in which works a pinion operated by the thumb screw f. This metal track D' is screwed to the face of the cross piece E, and dovetailed along top and bottom to receive the bearing frame of the reading microscope. Upon the top of the cross piece E two silver scales are mounted side by side, graduated from the central vertical axis outward along a radius in either direction, one reading to $\frac{1}{25}$ of a cm. and the other to $\frac{1}{50}$ of an inch, and by means of two corresponding verniers, which move with the reading microscope, the radial distance of any setting can be read to $\frac{1}{500}$ of a mm. or $\frac{1}{1000}$ of an inch.

The Reading Microscope.

The axis of the reading microscope is inclined at an angle of 45° to the vertical axis of the instrument, to permit reading from a sitting position, and thus avoid the strain consequent upon prolonged readings directly from above. This is accomplished by means of an inclined metallic mirror inside the vertical barrel of the microscope, which serves to reflect the light from the negative below into the eye of the observer at the eye-piece.

The cross hairs for the microscope are placed across the lower end of the vertical barrel, that they may be adjusted as near to the negative as possible to give increased accuracy; and since the glass negatives vary considerably in thickness, the whole microscope can be raised and lowered by means of the thumb screw *g*, and a scale for reading these relative heights is also provided. The system of cross hairs consists of two sets at right angles to each other, which have a relative motion in azimuth with respect to each other. They are mounted in separate collars at the lower end of the microscope barrel and are approximately in the same plane. By means of two pinions working in two cog wheels seen in the view and operated by two thumb screws *h* and *h'* on either side of the microscope, the two sets of hairs are moved in azimuth at will, and a circular divided scale *ii* reading to two degrees is provided by which the angle between the sets is known.

The advantage of this plan is that any arrangement of four hairs intersecting at a common point, found most convenient for the particular observer, or most desirable for accurate setting upon a particular form of record upon the plate, can be obtained by simply adjusting the thumb screws *h* and *h'* mentioned above. If the two sets are adjusted to coincide, we have the ordinary case of but two perpendicular cross wires visible, and from this to intersections at any angle with respect to each other, and also

at any angle with respect to the sharp edge of the record which is radial upon the plate, are obtainable.

To make this microscope more elastic and applicable to a wide range of purposes, it is provided with two sets of lenses proper and three different eye pieces, giving combinations in magnifying power of 3, 7, and 10.

For the purpose of illuminating the negatives to facilitate setting, two plane mirrors, M' and M'', placed to reflect light directly up through the negative into the microscope, are attached; and by means of the hand screws P and P' these may be adjusted to the proper angle to reflect the outside light.

The Micrometer Microscopes.

Instead of verniers and magnifying glasses for reading the angles, the much more convenient and accurate micrometer microscopes shown at R and R' are employed. As in the reading microscope, these are mounted with their axes inclined at an angle of 45° with the vertical axis of the instrument, so that all observations both for angles and for settings upon the record are conveniently performed by the observer from a sitting position and without moving. This is accomplished by means of totally reflecting prisms S and S', which reflect the light from below into the eye of the observer at the eye piece.

Through the outer rough circle M two windows are cut beneath the reflecting prisms of the micrometer microscopes, by which the illumination of the silver scale beneath is obtained from the light passing through the translucent glass cylinders T and T', and through these windows is the only way by which this scale can be observed. To prevent any particles of dust from collecting inside the tube, the lower end of each of the translucent glass cylinders is provided with a circular cloth screen extending to the surface of the outer scale circle M. These are shown at u and u'.

To enable the instrument to be used at night as well as in

daylight, the translucent cylinders can be artificially lighted by means of two small incandescent electric lamps shown at V and V'. These lamps require about five volts and one half an ampere to secure a good illumination of the scale beneath.

The silver scale is divided to read to tenths of a degree. The decimal division of a degree is preferred to minutes and seconds, because if the readings were taken in minutes and seconds, they would have to be reduced to the decimal system in computing velocities.

The micrometers WW' are divided into twenty parts; and since five revolutions of the micrometer screw correspond to one small division upon the scale beneath, the micrometer reads directly to one thousandth of a degree, and by estimation to tenths, to one ten-thousandth of a degree.

Centering the Glass Negative.

The circles which appear upon the tuning-fork records and are produced by the fine wires in the camera already described are for the purpose of accurately centhring the plate before any measurements are taken. This obviates any necessity for centering the plate itself when in position in the camera.

The negative is laid film side up upon the glass plate B, approximately centered and held in position by the four spring clamps *cccc*. By means of the traversing screw (f) the reading microscope is moved until the tuning fork record comes in the field of view, and then by means of the hand screws N and N' the plate B with negative is moved until the intersection of the cross hairs remains upon any one of the circles of the record during an entire revolution of the plate. The negative then being centered, the reading microscope may be traversed to show the chronograph record, and the setting made for the final readings of the angle by means of the micrometer microscopes already explained.

In considering this instrument as a whole, it is evident that it has a wide range of use other than that for which it was particularly constructed. How it can be employed either to divide or to test the division of graduated circles will readily be seen by those interested, and the convenience and arrangement of the various parts, and especially their simplicity, it is thought will commend this form of angle measuring instrument for a general laboratory apparatus.

Some Further Experiments with the Chronograph.

During the progress of the installation and testing of the new instrument an opportunity was presented for some further experiments with it, both along the line of simplification in manipulation when used for the single purpose of measuring projectile velocities, and also some other experiments of a more purely physical interest.

The design of the chronograph is such that it may be used for a variety of purposes not only as a chronograph, but also as an instrument for the investigation of problems which are met with in the laboratory, such as the study of alternating current phenomena, the study of the rate of motion of almost any body, the recoil of gun carriages, and many others which suggest themselves to the reader. The pleasure experienced in using a well made instrument with all its fine adjustments can be appreciated after one has been obliged to use the home made apparatus with which the original investigations were made.

The source of power which was permanently installed to operate the chronograph consists of 38 storage cells, which are charged at regular intervals by an Edison dynamo driven by a steam engine. The use of these cells for the chronograph does not prevent them from being available for the general laboratory uses of the Artillery School, as well as for furnishing the electric lighting for the electrical and chemical laboratories, the machine shops, boiler houses, and also for operating the two Boulengé

chronographs already at the post (thus supplanting the Edison-Lalande battery), the post telegraph and fire alarm systems (supplanting the large number of gravity cells formerly used), besides electric fans, etc.

Since storage cells have an internal electrical resistance practically *nil*, they can be drawn upon independently for all these purposes at the same time, or by means of a general switchboard each circuit can be cut out or thrown in at pleasure.

Two new No. 8 copper line wires, extending from the instrument to the new 10-inch disappearing gun-battery about 1100 yards distant, have been put up and are ready for use.

Exterior Velocities with the 3".2 Field Gun.

For the purpose of the preliminary tests with the new instrument and to determine the constants of the gravity switch, the field gun was again utilized as being most convenient, and on August 4th, 1896, the first actual velocity was taken. But four screens were employed, and these were placed at about ten foot intervals. The revolutions of the plate were 658 per minute, and the strength of current employed for the transmitter circuit, the four sections of the tube coil being joined in parallel, was 13½ amperes. The same construction of screens and means of restoring the transmitter circuit between screens was employed as is described in the first paper, and were all that could be desired for the purpose. The general appearance of the record is the same as has been shown in previous records, except that with a sensitive plate twelve inches square the linear distance between consecutive records, representing ten feet on the proving-ground, is much greater than formerly, and permits therefore even greater accuracy in measurement.

Simplification in the Use of the Instrument for Projectile Velocities.

To avoid the necessity of being obliged to cause the projectile records communicated by the transmitter to occur during

the passage of the camera drop shutter in its fall, which limits the total time of exposure of the plate, it is very desirable to be able to dispense with this shutter in ordinary practice in simply taking velocities, employing only the crossed Nicols to prevent the light beam from entering the slit before the transmitter circuit is made.

We are thus relieved of any uncertainty due to non-uniformity in the action of electric primers, or the difference in the "time interval" between the making of the primer circuit and the projectile reaching the muzzle for different guns, which intervals though ordinarily considered small are not so when compared with such intervals as are met with in ballistic experiments; and we are assured that whatever happens in the transmitter circuit *will surely* be shown upon the plate in any case, no matter what gun is being used.

If we also have some means of controlling the exposure of the tuning fork record without operating the camera shutter, and causing this record to be made upon the plate simultaneously with the chronograph records, we have an ideal simplicity in operation for taking projectile velocities.

A method which has been shown by trials to be entirely satisfactory is the following: The mounting for the fork F (Figs. 43, 44, and 45) is simply transferred to the same optical T rail with the lamp and tube, and placed between the analyzer and the receiver. The lens L''', which is used upon the fork rail for focussing the luminous hole in the aluminum foil upon the plate, is also placed upon the tube rail, and used to condense the light which comes through the tube upon the edge of one prong of the fork, which is now used without the aluminum foil attached and properly adjusted in the path of the beam, so as to intercept one side of it. The short focus lens L' is now used to form a sharp and magnified image of the edge of the fork upon the slit.

By this simple arrangement we see that each chronograph record becomes its *own time record* as well, and when once the fork and the lens L' are adjusted, the operator need have no

further concern during a series of observations upon the same plate in regard to securing the time record, other than providing that the fork shall be vibrating at the instant an observation is to be made, and this, too, is made entirely automatic and perfectly certain of execution.

The available space for other records upon the plate is now more than doubled, and there is no possibility of associating the wrong fork record with any particular gun record, but, if desired, a long series of observations can be taken without ever removing the plate holder from the camera wheel, and in regular succession from outside inwards, or *vice versa*, by simply traversing the rail slightly between shots by turning the traversing hand-screws provided for the purpose.

When it is desired to use the camera in this manner without operating the drop shutter provided, it is only necessary to secure the shutter temporarily in any position, so that its opening *R*, Fig. 47, shall uncover the slit, and to close entirely the round opening for the fork record on the opposite side, shown at *K*, Fig. 50, shift the slides *N* and *U* until this obtains.

To prevent the daylight of the room from fogging the plate through the open slit, and it would have an especial opportunity if the slit should be exposed to it during several revolutions of the plate before the gun was fired, it is desirable to provide means by which the time between the instant at which the gun is fired and the slit itself exposed shall be as short as possible, and fortunately this is accomplished very easily.

All that is necessary is to pull a simple hand switch, which will close the transmitter circuit, to admit the light through the tube upon the plate, at the same time that the primer circuit is closed to fire the gun. The same battery which is used for the tube is also used to fire the primer.

From this it is but a natural step to attach to this same lever the wedge which plucks the fork, and we have reached the point at which the whole operation of taking with certainty observations for velocities at any number of prepared points either out-

side or inside the gun consists in simply moving one hand lever.

The lamp is kept adjusted and the camera wheel constantly revolving, so that whenever the telephone from the proving ground announces that the shot can be fired, the chronograph operator accomplishes all with the simple act above described. Furthermore, this plan permits of all this information being recorded upon the plate by means of but *two line wires* from the chronograph to the gun, which may be any desired distance away, because the same wires may now serve for the primer and transmitter circuits, they being closed at the same time by the movement of the firing lever. By this means we have upon each record the additional information of the exact "time interval" between the making of the primer circuit and the instant the projectile reaches the muzzle or first prepared screen, which "time interval" varies for different guns, kinds of powder, etc., and is a constant itself of considerable importance, especially in naval gunnery from a rolling platform.

Numerous tests were first made to prove by actual trials whether, when the Nicols were set for extinction, this served as a sufficient screen to prevent the powerful beam condensed down the tube from still being able to fog the plate after a time sufficient for several revolutions of the plate, as also to determine to what extent the ordinary daylight of the room must be screened off to secure clear records without traces of fog. The small slide windows in the wooden face cover of the camera are convenient means of making the exposure by hand when the *inside drop shutter* is not operated.

In Fig. 52 are shown some of the "combination records" by the method described above, in which the tuning fork 250 (single) vibrations per second is employed. The plate was revolved slowly by hand, which accounts for the saw tooth appearance of the record. The exposure for this plate was made by the slide window above referred to.

Fig. 53 shows part of an actual velocity record by this plan

with the 3.2" gun, in which the tuning fork 500 (single) vibrations per second was used. The four sections of the tube coil were joined in series, and a current of seven amperes used in the transmitter circuit to increase the amount of light through the analyzer.

Second Method.

Another way to accomplish the result above described has some advantages over the one just mentioned; for this allows a tuning fork record to be taken as formerly. The former tuning fork records, with their fine intersection points by which measurements are made, are difficult to improve upon, and some advantage is gained by retaining it. This may be done by having the shutter for the tuning fork record work independently of that for the chronograph record. The chronograph shutter is then left permanently open, and only the Nicol prisms and tube used for a shutter as previously described. The gravity shutter is used for the tuning fork, which is released when the lever is pulled to fire the gun. This gives an independent time record as formerly, and if many exposures are made on the same plate care must be taken to be sure which records go together.

The chronograph record, with the exception of the one wavy edge, will be the same as last described. The transmitter circuit is made with the primer circuit, and the "time interval" of the particular gun used is recorded on the plate as before.

Some Chronograph Experiments with Alternating Currents.

The enormous commercial development of alternating currents during the past few years has necessitated a thorough study of the phenomena connected thereto. The great difficulty which has stood in the way of experimentally recording by a continuous method, not a method by points, the instantaneous values of an

alternating electric current which is changing its direction hundreds of times a second, at present constantly met with in practice, has prevented in a great measure direct experimental evidence being obtained to verify and corroborate many of the conditions which theory points out should exist.

This experimental problem becomes much more difficult, when we attempt to determine and record what happens in a circuit carrying an alternating current, when it is suddenly altered in some way, as, for instance, when it is made or broken. The fluctuation of the current under varying conditions of the circuit as to its resistance, inductance, and capacity when the circuit is made, has been theoretically deduced when the electromotive force is truly harmonic, and this case is especially worthy of experimental evidence.

Any "method by points" depends fundamentally upon the supposition that the fluctuations in current repeat themselves exactly in successive alternations, and evidently this is far from being true for the important cases just mentioned.

The employment of a continuous method of recording, not involving the movement of any *ponderable matter*, and therefore without inertia in the production of the record, which is the fundamental principle of this chronograph, gives indications therefore in accurate phase with the fluctuating current, no matter how rapid these changes may occur, and since the time scale is also accurately recorded upon the plate by means of the tuning fork record, we may consider each negative obtained as a qualitative graphical representation of the varying current, automatically plotted in terms of the two variables, time and intensity.

It is true that the values of intensity shown are not to scale, nor is the law of its actual intensity variation definitely shown upon the negative; but, nevertheless, the main features of the problem are recorded, and these are more often all that are desired. For instance, whenever the current is zero there is no magnetic field within the tube solenoid, and consequently no

rotation of the plane of polarization of the beam, and therefore no light upon the plate.

Between the points of 0° and 90° rotation it can be said that the intensity of light which reaches the plate varies in a general way with the sine of the angle of rotation. As is well known, however, what has been said only strictly applies to monochromatic light and to the intensity of light which reaches the plate, not to the photographic record produced by it, since from the researches of Verdet and others it is known that the component rays of white light are rotated by a given magnetic field in different amounts. This rotation depends not only upon the wave-length, but upon the index of refraction of the particular medium corresponding to that wave-length, and also upon the rate of change of the index with respect to the wave-length. Furthermore, it is known that the actinic value in producing photographic results is not the same throughout the spectrum, but is richer in the blue end.

These refinements, however, possess little significance when we are concerned only with the general features of the problem, and care less about absolute values of the varying current as in the case at hand.

Apparatus employed.

The principal source of power for alternating current work at hand in the laboratory is a 300 light Fort Wayne ten-pole alternator, producing a difference of potential at its terminals of a thousand volts. By means of a bank of commercial transformers this voltage is reduced as desired for ordinary experimental purposes. An alternating source of potential of about 300 volts was usually employed in the experiments to follow, as being safe enough to handle and high enough to secure good results upon the plate.

This voltage was obtained by joining in series the secondary coils of five transformers ranging in voltages from 50 to 100,

their primary coils being as usual each connected to the dynamo mains. A measured voltage of 304 at normal speed was thus obtained for use. The inductances of the secondary coils were measured to be as follows:

Secondary	coil	transformer	No. 1	.0435	henrys
"	"	"	No. 2	.0831	"
"	"	"	No. 3	.0431	"
"	"	"	No. 4	.0605	"
"	"	"	No. 5	.1399	"

$$\text{Total inductance} = 0.3701 = \Sigma L$$

To obtain the requisite number of ampere turns around the tube to produce good results for a given source of impressed alternating E. M. F., it is necessary to consider not only the ohmic resistances of the line and the coil itself, but also the inductances of the line, transformer secondary coils, and tube coil, as well as any capacity that may be present or introduced into the circuit. Accordingly, the source of alternating E.M.F. being determined, suitable transmitter coils were designed and made for these experiments, the constants of which are given below.

Coil A.

Size of copper wire, No. 36, single silk covered.
Length of coil, 36.2 centimeters.
Number of turns, 13670.
Resistance, 1310 ohms.
Inductance, .875 henrys.

Dimensions of carbon bisulphide tube for Coil A:
Total length of glass tube, 40 cms.
Outside diameter, 2 cms.
Inside diameter, 1.5 cms.

Coil B.

Size of copper wire, No. 28, double cotton covered.
Length of coil, 36.5 centimeters.
Number of turns, 11,168.
Resistance, 390 ohms.
Inductance, 0.66 henrys.

Dimensions of carbon bisulphide tube for Coil B:
Total length of glass tube, 39.5 cms.
Outside diameter, 2.5 cms.
Inside diameter, 2 cms.

The first experiments were to obtain records upon the camera plate of the simple alternating current, and to note the effect of variations of speed of the plate and width of slit upon the appearance of the record. Fig. 54 exhibits a number of such records and illustrates the variations referred to. The speed of the generator was such that the transmitter current had a frequency of about 137 periods per second, and to avoid drawing out the records too much, most of the exposures were taken with the camera wheel revolved slowly by hand instead of using the electric motor.

In the figure there are seven different exposures made on the same plate by moving the T-rail of the chronograph each time, so that the beam of light strikes the plate at different distances from the center. The exposures are purposely made under different conditions, merely to illustrate the different appearance which the records assume. The circuit in each instance contains Coil B above described, and the source of supply of current was the secondaries of five transformers joined in series, giving a total of 300 volts at frequency 137 complete alternations per second. Beginning at the outside, the records may be thus described.

1. The camera slit was comparatively wide, the speed of rotation moderate. No condensers in circuit.

2. Slit same width, speed somewhat faster. Three condensers are inserted in series with the circuit, making a capacity of 4.785 micro-farads.
3. Same circuit as 2 above, but camera slit is narrower. Speed of plate is decreased.
4. Same circuit as 2 above, slit wide, speed increased considerably.
5. Same circuit as 2 above. Narrowest slit of all. Plate moved very slowly.
6. Same circuit. Very narrow slit. Speed moderate.
7. No condensers in circuit. Very wide slit. Faster speed of plate. In this case the plate went more than once around making a double exposure.

The ammeter-voltmeter method was used to measure the inductances of the coils above referred to, which may be illustrated by the case of Coil B.

The equation for current in a circuit containing an alternating electromotive force with resistance, inductance, and capacity is

$$I = \frac{E}{J} = \frac{E}{\sqrt{R^2 + \left(\frac{1}{C\omega} - L\omega\right)^2}}, \tag{1}$$

in which the impedance J, is made up of two terms, the ohmic resistance R and the reactance $\frac{1}{C\omega} - L\omega$. In the case of coil B, since there is no capacity in the circuit, the reactance is entirely inductive and reduces to $L\omega$. Making this simplification and solving for L, we write

$$L = \frac{1}{\omega}\sqrt{\frac{E^2}{I^2} - R^2}, \tag{2}$$

in which the second member contains only measurable quantities.

The angular velocity $\omega = 2\pi n$, in which n is the number of complete cycles per second. The speed of the generator was such that $n = 139$ and $\omega = 873$. $E = 84.5$ obtained from voltmeter reading at terminals of the coil. $R = 390$ ohms measured by Wheatstone bridge.

Since the current I was too small to be directly measured with the alternating current ammeters at hand, resort was made to the voltmeter for the current value also. A non-inductive resistance of 144 ohms, consisting of incandescent lamps, was joined in series with the circuit, and the voltmeter reading taken at the terminals of this resistance was = 17.5.

We then have

$$I = \frac{17.5}{144} = 0.1214 \text{ amperes.}$$

Substituting these measured values in (2) above, we have

$$L = \frac{1}{873}\sqrt{\frac{84.5^2}{.1214^2} - 390^2}.$$

$$= 0.66 \text{ henrys.}$$

The capacity at hand for use in these experiments was a set of six commercial Stanley condensers, capable of standing continuously 500 volts alternating. These condensers were approximately alike, each having a measured capacity as follows:

The six condensers were themselves joined in parallel, and then connected in series with an ammeter directly to the transformer terminals. Equation (1) for this case, where R and L are each zero, becomes

$$I = \frac{E}{\frac{1}{C\omega}} = C\omega E;$$

or

$$C = \frac{I}{E\omega}.$$

Simultaneous ammeter and voltmeter readings gave $I = 2.5$ and $E = 304$, and the speed of the alternator was such as to make $\omega = 860$. We therefore have

$$C = \frac{2.5}{304 \times 860} = 9.57 \times 10^{-6} \text{ farads},$$

$= 9.57$ microfarads $=$ capacity of six condensers in parallel.

$\therefore$ Capacity of each condenser $= 1.595$ microfarads.

Experiments upon Currents at the "Make" for an Harmonic E. M. F.

A number of negatives were taken with the chronograph to verify the results of theory in the interesting case of "make" for an alternating current, or, in other words, to determine the effects upon the current during the very short interval of time after the harmonic electromotive force is suddenly introduced into the circuit. Transmitter circuits were made up containing resistance, inductance, and capacity in varying proportions, and the effects recorded on the plate upon making the circuit.

When any electric circuit is closed, the moment at which actual contact is made is usually a very short interval of time as compared with the period of alternation of any ordinary alternator. Evidently, then, the circuit may be closed when the harmonic electromotive force is at any point of its phase, that is, it may be zero, may have its maximum value, or any intermediate value.

The effect upon the flow of current for a given circuit is known to depend, among other things, upon the phase of the electromotive force at the instant the circuit is made. Figs. 55 to 60 show some of the results where the circuit is made, which

are in accord with the indications of theory.* Figs. 55, 56, and 57 show different exposures for a circuit including chronograph tube-coil B, the secondaries of the five transformers, and the six Stanley condensers in parallel with each other and in series with the circuit, under similar circumstances of "make."

The constants of this circuit were:

Circuit I.

$$\Sigma L = 0.37 + 0.66 = 1.03 \text{ henrys};$$
$$\Sigma C = 9.57 \times 10^{-6} \text{ farads};$$
$$\Sigma R = 390 \text{ ohms}.$$

$$E = 300 \text{ volts} = 300 \times 10^{8} \text{ C.G.S. units};$$
$$R = 390 \text{ ohms} = 390 \times 10^{9} \text{ C.G.S. units};$$
$$L = 1.03 \text{ henrys} = 1.03 \times 10^{9} \text{ C.G.S. units};$$
$$C = 9.57 \text{ microfarads} = 9.57 \times 10^{-15} \text{ C.G.S. units};$$
$$\omega = 865.$$

The general expression for the instantaneous value of the current flowing in any circuit containing resistance, inductance, and capacity is given by the equation

$$(1)\quad i = \frac{E}{\sqrt{R^2 + \left(\frac{1}{C\omega} - L\omega\right)^2}} \sin\left\{\omega t + \text{arc-tan}\left(\frac{1}{RC\omega} - \frac{L\omega}{R}\right)\right\} + c_1 \epsilon^{-\frac{t}{T_1}} + c_2 \epsilon^{-\frac{t}{T_2}},$$

in which c_1 and c_2 are arbitrary constants, and T_1 and T_2 are the time-constants of the circuit. Usually the last two terms of this equation are not written, for when the alternating current

* The discussion of currents at the "make" for an harmonic E. M. F. may be found in Alternating Currents, Bedell and Crehore. W. J. Johnston Company, New York.

has reached a steady state the value of these terms becomes inappreciable. This steady state is usually reached in a very few oscillations after the "make," but in the present investigation it is the effect of these exponential terms at the "make" which it is desired to study. The values of the time-constants T_1 and T_2 depend upon the constants of the circuit R, L, and C, according to the equations

$$T_1 = \frac{2LC}{RC - \sqrt{R^2C^2 - 4LC}},$$

$$T_2 = \frac{2LC}{RC + \sqrt{R^2C^2 - 4LC}}.$$

It sometimes happens that the constants are such that the values of the time-constants T_1 and T_2 have imaginary forms. This is the case when $4L$ is greater than R^2C. It has been shown, however, that when these time-constants assume the imaginary form the two terms at the end of equation (1) above, when taken together, may be expressed in a real form involving a sine function instead of an exponential one. This form may be written

$$(2) \qquad A\epsilon^{-\frac{Rt}{2L}} \sin \left\{ \frac{\sqrt{4LC - R^2C^2}}{2LC} t + \Phi \right\},$$

where A and Φ are the arbitrary constants instead of c_1 and c_2 above. The coefficient of t in this expression is equal to 2π times the *natural* frequency of oscillation of the circuit, and if denoted by α, the above expression becomes

$$(3) \qquad A\epsilon^{-\frac{Rt}{2L}} \sin \left\{ \alpha t + \Phi \right\}.$$

Writing in equation (1) the abbreviated values

$$(4) \qquad I = \frac{E}{\sqrt{R^2 + \left(\frac{1}{C\omega} - L\omega\right)^2}}$$

and

$$(5)\qquad \theta = \text{arc-tan}\left(\frac{1}{RC\omega} - \frac{L\omega}{R}\right),$$

we have

$$(6)\qquad i = I \sin\left\{\omega t + \theta\right\} + A\epsilon^{-\frac{Rt}{2L}} \sin\left\{\alpha t + \Phi\right\}.$$

The arbitrary constants A and Φ must be determined according to the physical conditions imposed by the problem. In this equation time is counted from the moment when the harmonic E. M. F. is zero. Physically, the circuit may be closed at any instant, and previously to the closing of the circuit no current is flowing. One condition which determines the constants is, therefore, that when $i = 0$, $t = t_1$, meaning by t_1 the time when the circuit is closed counting from when the E. M. F. is zero. The charge Q of the condenser is also supposed to be zero when the circuit is made. The angle $\omega t + \theta$ in equation (6) may be denoted by ψ, and if ψ_1 denotes the value of this angle when $t = t_1$, then the equation may be written in full with constants determined according to the above conditions,

$$(7)\quad i = I \sin\psi + \frac{2I\sqrt{(LC\omega^2 - 1)\sin^2\psi_1 + \frac{1}{2}RC\omega \sin 2\psi_1 + 1}}{\omega\sqrt{4LC - R^2C^2}}$$

$$\epsilon^{-\frac{R}{2L}(t-t_1)} \sin\left\{\alpha(t - t_1) + 180^\circ + \text{arc-cot} - \left[\frac{2\cot\psi_1 + RC\omega}{\omega\sqrt{4LC - R^2C^2}}\right]\right\}.$$

Physically, we may say, from an inspection of this equation, that the true current wave is the sum of two simple waves, each expressed by a single term in the equation. The first is an harmonic wave, $I \sin\psi$, which is the final steady form to which the current approaches. This is evident, for the second term contains ϵ, the Naperian base with a negative exponent, so that as t increases the whole term rapidly decreases until its effect is practically *nil*. The rapidity of this decrease is governed by

the value of $\frac{R}{2L}$ found in the exponent of ϵ. Usually these values are such that the rate of decay is very rapid. The coefficient of ϵ, which determines the magnitude of the initial value of the logarithmic curve, is seen to depend largely upon the value of ψ_1, that is, upon the time t_1, when the circuit is closed. With the same circuit and E. M. F. it is evident that very different results may be obtained by closing the circuit at different times.

The whole second term represents a sinusoidal curve having a logarithmic decrement, and this curve at the time t_1, when $i = 0$, must therefore have its initial ordinate equal and opposite to the value of the first term, $I \sin \psi$, of the equation in order to satisfy it. When the numbers are substituted in equation (7), representing the constants of the circuit previously given, we have

$$(8)\ i = 0.493 \sin \psi - 0.2435 \sqrt{6.4 \sin^2 \psi_1 + 1.61 \sin 2\psi_1 + 1}$$
$$\epsilon^{-189(t-t_1)} \sin \left\{ 237(t - t_1) + 180° + \text{arc-cot} - \left[\frac{2 \cot \psi_1 + 3.22}{5.74} \right] \right\}.$$

If the value of t_1 is such as to make $\psi_1 = 0$, this equation becomes

$$(9) \quad i = 0.493 \sin \psi + 0.2435 \epsilon^{-189(t-t_1)} \sin \left\{ 237(t - t_1) \right\}.$$

The plot of this equation is represented by curve (III), Fig. 61. This curve is made up of two component curves, one corresponding to each term of equation (9), the first term giving curve (I) and the second term curve (II). The sum of these curves gives curve (III), which is the resultant curve representing the resultant current equation (9). Curve (I) is a sine curve having a maximum amplitude of 0.493 amperes, and a period of 0.007275 seconds corresponding to the impressed frequency of 137.5. Curve (II) is a sine curve with logarithmic decrement. Its period is comparatively long, being 0.0265 seconds corre-

sponding to the slow frequency of 37.5 per second. The initial value of the logarithmic curve (IV) is 0.2435, the coefficient of the second term in the equation, and the rate of decay is determined by the exponent -189, such that the ordinate has $\frac{1}{\epsilon}$ of its initial value after 1/189, or .0053 of a second. This time-constant is indicated in the figure by a vertical line drawn at the distance 0.053. The phase of oscillation is seen to be zero, that is, the logarithmic oscillation begins with the zero value. This is evident for another reason also. The initial value of the curve representing the second term must be equal and opposite to the initial value of that representing the first term, since their sum must give an initial value of zero for the resultant current curve, to fulfil the physical conditions. A sine wave curve (V) is drawn representing the wave-length and amplitude of the oscillation as it would be if not subject to the logarithmic damping. It is of use in constructing curve (II); for the points on curve (II) are found graphically by diminishing the ordinate of the logarithmic curve at any point in the ratio of the ordinate of the sine curve at that point to its maximum value. The resultant curve (III) representing equation (9) is seen to have first a slightly larger wave than the normal wave, then a considerably smaller one, and the third wave very nearly coincides with the normal wave curve (I), so that beyond the fourth semi-period the disturbance due to the "make" has become imperceptible.

An experiment with the same conditions of circuit in every respect, except that the time of making the circuit alone is different, will give entirely different results, as before mentioned, dependent upon the phase of the E. M. F. at the instant of make. A number of cases have been calculated from the equations and represented in Figs. 61, 62, 63, and 64. These figures correspond to different times of make, or to different values of the angle ψ_1 in the equation. The cases represented in the figures correspond to the values of $\psi_1 = 0°$, $45°$, $90°$, and $135°$ respectively. It is seen that the initial value of the

logarithmic curve (IV) depends upon ψ_1. A curve (VI) is shown in the figures to indicate the value of the initial ordinate of the logarithmic curve for all values of ψ_1. This curve is the same in the four figures. Curve circuit I, Fig. 69, has been constructed to represent equation (10) below, which when multiplied by the coefficient 0.2435 gives the initial values of the logarithmic curve for different points of the phase. This curve shows the values of ψ_1 which give maximum and minimum values of the logarithmic curves. These are seen to be neither the zero nor the ninety degree values of ψ_1, but the values 76° 37'.5 for a maximum and 166° 37'.5 for a minimum.

The equation of this curve, circuit I, is from equation (8) seen to be

$$(10) \qquad y = \sqrt{6.4 \sin^2 \psi_1 + 1.61 \sin 2\psi_1 + 1},$$

which might be written

$$(11) \qquad y = \sqrt{a \sin^2 \psi_1 + b \sin 2\psi_1 + 1}.$$

Differentiating (11) and equating to zero for a maximum, we have the condition that

$$2a \sin \psi_1 \cos \psi_1 + 2b \cos 2\psi_1 = 0,$$

or

$$a \sin 2\psi_1 + 2b \cos 2\psi_1 = 0,$$

or

$$(12) \qquad \tan 2\psi_1 = -\frac{2b}{a}.$$

Applying this general condition for maximum or minimum to (10) above, we have

$$\tan 2\psi_1 = -\frac{2 \times 1.61}{6.4} = -0.504,$$

or

$$\psi_1 = 76^\circ\ 37'.5 \text{ or } 166^\circ\ 37'.5.$$

The maximum and the minimum points are thus 90° apart.

The frequency of the oscillation of the sine wave represented in curve (V) is determined in equation (7) by the coefficient α, whose value is shown in equation (2). This depends upon the constants of the circuit only, and remains always the same for any circumstances of make for the given circuit. The frequency calculated for this case is 37.5 complete oscillations per second.

Another important question is the phase at which the oscillation within the logarithmic curve begins. This must be known in order to draw the sine curve (V) in proper position upon which depends curves (II) and (III). This relation is shown in equation (7) to be

$$(13) \qquad x = 180^\circ + \text{arc-cot} - \left[\frac{2 \cot \psi_1 + RC\omega}{\omega\sqrt{4LC - R^2C^2}}\right],$$

and it therefore depends upon ψ_1. In the example just given, where $\psi_1 = 0^\circ$, $\cot \psi_1 = \infty$. Hence the phase was 360°, or the same thing, 0°. By plotting equation (13) this general relation of the phase for any value of ψ_1 is shown.

To sum up what has been said concerning the equations and figures in this case, the general equation (7) applies to any condition of circuit or "make." In the case of the particular circuit named the equation reduces to (8), which applies to any circumstance of "make" for that circuit. The four cases represented in Figs. 61, 62, 63, and 64 correspond to the four cases of "make" when $\psi_1 = 0^\circ$, 45°, 90°, and 135° respectively. These curves have four corresponding equations derived from (8) above. These equations are, first, equation (9) above, which applies to the case $\psi_1 = 0$. The other three equations which have not yet been given are:

for $\psi_1 = 45°$,

$$(14) \quad i = .493 \sin \psi + .587 \epsilon^{-189(t-t_1)} \sin \left\{ 237(t-t_1) + 322° \, 16' \right\};$$

for $\psi_1 = 90°$,

$$(15) \quad i = .493 \sin \psi + .662 \epsilon^{-189(t-t_1)} \sin \left\{ 237(t-t_1) + 308° \, 34' \right\};$$

for $\psi_1 = 135°$;

$$(16) \quad i = .493 \sin \psi + .400 \epsilon^{-189(t-t_1)} \sin \left\{ 237(t-t_1) + 286° \, 49' \right\}.$$

Referring to the photographs shown in Figs. 55, 56, and 57, it is seen in each case that the record starts with a very small spot of light, and next follows a very large spot, then a smaller one followed by a larger, until they are finally equalized. Each figure shows two reproductions from the same plate, the small figure placed just below the large one being the actual size of the record as taken, and the large figure is an enlargement from the smaller one. In the process of enlarging, the figure is reversed so that the enlarged picture reads from right to left and the natural sized one from left to right. These three figures correspond fairly well to those shown in the drawing, Fig. 62, where it is seen that the resultant wave curve (III) exhibits the same general succession of waves, as shown in the photograph.

Circuit II.

As representing another distinct case corresponding to a different circuit from that just discussed, a view is shown in Fig. 58 of the result obtained from a circuit the same as that previously described, except that half the number of condensers are used, making the capacity 4.78 microfarads.

Referring to equation (7) and substituting the values of the constants for this second case, we obtain the equation

(17) $$i=0.560 \sin \psi+0.332 \sqrt{2.68 \sin^2 \psi_1+0.805 \sin 2 \psi_1+1}$$
$$\epsilon^{-189(t-t_1)} \sin \left\{ 396(t-t_1)+180°+ \text{arc-cot} - \left[\frac{2 \cot \psi_1+1.61}{3.38}\right]\right\},$$

which corresponds to (8) above.

Calculating the values of the radical expression for different values of ψ_1, a curve, circuit II, Fig. 69, corresponding to curve circuit I, of the first case is constructed, which when multiplied by the coefficient 0.332 gives the initial values of the logarithmic curve for different points of the phase. The maximum value of the logarithmic curve in this case is 0.654, corresponding to the value 0.680 of case I. The minimum value is 0.292, corresponding to 0.191 of the previous case. These values occur at the angles $\psi_1 = 74°$ for a maximum, and $\psi_1 = 164°$ for a minimum.

The natural frequency of oscillation in the circuit is increased, by using three condensers instead of six, to sixty-three complete oscillations per second, corresponding to the period 0.01586 of a second.

The four cases corresponding to the values of $\psi_1 = 0°$, 45°, 90°, and 135° respectively are shown in Figs. 65, 66, 67, and 68. These are represented by the equations:

(18) For $\psi_1 = 0$,
$$i = 0.560 \sin \psi + 0.332\epsilon^{-189(t-t_1)} \sin \left\{ 396(t-t_1) \right\}.$$

(19) For $\psi_1 = 45°$,
$$i = 0.560 \sin \psi + 0.588\epsilon^{-189(t-t_1)} \sin \left\{ 396(t-t_1) + 317° \; 9' \right\}.$$

(20) For $\psi_1 = 90°$,
$$i = 0.560 \sin \psi + 0.637\epsilon^{-189(t-t_1)} \sin \left\{ 396(t-t_1) + 295° \; 28' \right\}.$$

(21) For $\psi_1 = 135°$,
$$i = 0.560 \sin \psi + 0.411\epsilon^{-189(t-t_1)} \sin \left\{ 396(t-t_1) + 263° \; 22' \right\}.$$

It is seen that the photograph, Fig. 58, which is a chronograph record using this circuit, has first, beginning on the right

of the enlarged view and on the left of the natural-sized one, a small spot and then a second a little smaller, and the third larger than the average and the rest about the average. This corresponds well with the drawing, Fig. 66, and to equation (19), where $\psi_1 = 45°$.

Figs. 59 and 60 are taken with the same circuit as above, except that the condensers were entirely removed from the circuit. Here the enlarged view and the natural-sized one are each read from the same side, namely, the left-hand side. The first wave alone appears larger than the normal, and they then become uniform.

This also corresponds exactly with what is expected theoretically. There is this difference, however, between the cases, which is interesting tc note. There is no oscillation of the current at the "make," but simply a gradual change according to the logarithmic curve. The interesting feature is that this logarithmic curve may have a zero value for a certain value of ψ_1, while the circuits containing condensers have only minimum values.

Conclusion.

In closing this paper, which, in the sense that a chronograph based upon this new principle has now been constructed, installed, and tested in actual practice, naturally marks a distinct step in its progress, we cannot refrain from submitting a few observations both upon its future field of usefulness as a military instrument of precision, and also some of a more general character which have been especially emphasized during the progress of the experiments. The experiments thus far recorded have necessarily been of a superficial character, because it has been impossible for us to be together for but very brief periods at wide intervals apart. This accounts in part for lack of consecutiveness and systematic thoroughness of treatment, which is much to be desired in physical research. But in using the small time thus far available the object has been rather to indicate

the range of application of this new instrument than to exhaustively treat any one application, in the hope that in the interest of science others having more time and facilities than ourselves may possibly be induced to work with it and discover new fields for its use.

Gunnery Problems.

From one point of view it may perhaps be said that the greatest difficulty which the ordnance engineer has to contend with is that he is required to design and construct for a class of phenomena distinct in themselves, which are so rapid in their action and effects that all ordinary methods and tests of material cannot be relied upon for safe constructions without uncertain and undetermined factors of safety. Where the bridge engineer is supplied with accurate data the ordnance engineer is involved in more or less theoretical hypotheses. At this time not only is the actual amount of pressure developed in a gun undetermined, but the progressive effects of this pressure upon the various tubes and hoops of a built-up gun are also mooted questions.

The reason for this, it is needless to mention, is that, since there is no blow however sudden but which is progressive in its action, reliable experimental data are not obtainable, because the unit of time which can be reliably and consecutively recorded and measured is too great for the class of phenomena involved. It seems, then, that throughout ballistic experiments, from the motion of the projectile even to the behavior of the carriage under fire, the *one essential* element where the greatest error should occur in the data is in the measurement of the time.

The Unit of Time.

From a physical point of view it may be remarked that the time unit, unlike the units of length or mass, is in a sense a derived unit. Unlike the standard meter or gram, which can be directly examined, compared, and copied, we can have no direct

model of a second, but must *derive* the unit second by observations upon the motion of some standard body, such as a pendulum or the earth. This process of observing the motion of the standard body involves the recording of the exact instant between two or more points of the motion of the body which successively repeat themselves. Ultimately, where we are concerned with very minute intervals of time, the reliability of the method depends largely upon the ability to produce a record of the phenomena at a distance as nearly simultaneously with the occurrence of the phenomena itself as possible. Divested of details, it may be said that the *essential point* of this chronograph, whereby it is thought a distinct advance is made, is, that it places the reliable measurement of minute intervals of time upon a new basis, and opens up in consequence a range of experiment hitherto closed.

Exterior Velocities.

Although not yet actually accomplished with guns of larger caliber for lack of opportunity, yet there is no reason to doubt that ordinary exterior velocities can now be taken within a few feet of any of our modern guns regularly mounted in barbette or upon disappearing carriages. This will permit measurements, which have heretofore been limited to a proving ground on account of the great height and distance of ballistic screens which would be necessary in front of a modern parapet, to be taken directly upon the parapet at any fort and at any time in connection with the regular gun practice.

Although the blast of a modern high-power gun is terrific in force, yet when the prepared points can be as near together as is desired, the problem is at once shifted from the chronograph itself to the distant gun, where it becomes a matter of constructing such a screen frame as is found necessary by trial to withstand the blast, being always assured that whatever the projectile causes to happen in the transmitter circuit will be found faithfully and accurately recorded upon the receiver of the instrument.

For instance, there is no reason, if it is found necessary, why a steel screen frame a few feet in length sufficient to bear three or four small ballistic screens could not be constructed and made attachable to a permanent bed-plate foundation upon the parapet itself, or even that a distance of four or five feet of the length of the bore of the gun at the muzzle could not be permanently prepared during fabrication with perforations such as Nobel and Able employed to be used for taking velocities whenever desired. This would not materially impair the efficiency of the gun, and since the interruptions in the transmitter circuit would then always occur at the same carefully prepared points, not only would the calculations be abridged, but the transmitter circuit would be complete by attaching flexible wires to permanent binding-posts upon the side of the gun chase.

Furthermore, since it has been shown in the case of the 3″.2 field rifle that the velocity of the projectile from the muzzle of the gun to a considerable distance along the trajectory passes through a maximum value, it seems that the meaning of "initial velocity" should be more carefully defined, especially as the acceptance or rejection of a lot of powder from the manufacturer sometimes depends upon a very few feet more or less of initial velocity shown under test.

Interior Velocities, etc.

Opportunity has not yet been presented for experiments with larger guns upon the motion of projectiles inside the bore of the gun—a subject the importance of which is unquestioned—since the chronograph at the Artillery School is the only one as yet installed.

As stated above, the problem to be attacked for these guns is now at the gun and not at the chronograph, and it is hoped that this work can soon be seriously taken up at a proving ground where facilities for systematic and continuous work are available.

It may be remarked that projectile velocities are greater than those of any other body propelled by engines made by man, and the direct experimental study of their motion is, in consequence, correspondingly difficult. To obtain observations such as have already been given in a previous paper upon experiments inside the bore of the 3″.2 field gun, it was necessary to deal with a unit of time which bears about the same relation to a second as a second does to a third of an hour. In the case of the study of the recoil of gun carriages or the motion of pistons in hydraulic cylinders in general, the velocities being inversely as the masses, these motions are then so slow when compared with that of the projectile, that they should easily yield to a thorough experimental treatment.

Furthermore, if the motion of a projectile through the bore can be determined by a direct dynamic method, a gun would seem a good physical apparatus with which to study the laws of the thermodynamics of gases under adiabatic expansion.

A Laboratory Apparatus.

The brief account given in this paper of the application of this chronograph to the study of purely physical problems in the laboratory indicates, it is thought, its usefulness in this field. The rapid advance which alternating currents and alternating current machinery have made in the industrial world has led to a thorough theoretical study of the subject, but the experimental verifications have been attended with difficulty on account of the very rapid changes in current which must be continuously followed and recorded even with the lowest commercial frequencies. This difficulty is multiplied when, as in the experiments above, it is attempted to follow what happens during the very short interval after the "make" of an alternating current in a circuit containing varying conditions as to resistance, inductance, and capacity.

The design of a chronograph based upon this principle for general physical laboratory purposes would probably differ in

some respects from the one described in this paper, and possess attachments and adjustments not provided for in this instrument, but when carefully considered from this point of view, it is thought that this chronograph would prove a most useful apparatus in the equipment of a physical laboratory.

APPENDIX.

A RELIABLE METHOD OF RECORDING VARIABLE CURRENT CURVES.*

INTRODUCTION.

A PRACTICAL problem that has in more recent years presented itself to the electrician and physicist alike is: "How shall we measure the exact current which flows in a conductor at any instant of time, and record all the irregular changes to which it is subject?" Probably every one who has thought of such matters at all has considered this problem in some of the phases which it presents. The importance of the question, since the introduction and extensive use of the alternating current, has emphasized the fact that we need a "reliable method" of measuring the instantaneous values of a variable current, which is not a "method by points," but "a method which continuously records the current."

Under "a method by points" is included any method in which the current is obtained from readings (usually of an electrostatic voltmeter) due to the charge of a condenser which may be taken at any point of time. The essential characteristic of the method is that the current is *supposed* to repeat itself exactly during successive periods, or more generally when the conditions are exactly repeated. There can be no doubt that the

* A paper presented at the Annual Meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., May 17, 1894, by Dr. Crehore.

current *does repeat* itself under exactly similar conditions, but can we be sure that those conditions *are exactly repeated?* By this method a number of points are found, the time occupied being at least several minutes, and the collection of points properly arranged is a representation of the current during as short a time as the one-hundredth of a second, perhaps. Yet this method has proved to be a very useful and practical one, and has given us information concerning the currents and potentials of generators and transformers which is of paramount importance. Yet all will agree that this "method of points" is too limited in its application, and does not show us any sudden temporary change taking place in a current which does not *repeat* itself. Such, for instance, as a sudden "make," or "break," or "change" in an alternating current would not be easily shown by this method. The second method, previously designated "*a method which continuously records the current*," is the one to which this paper more particularly refers. Under this head are included all methods which attempt to record the current by causing it, either directly or indirectly, to move a material "something" so that its displacement is some single-valued function of the current. As an example of this method may be mentioned the well known experiments of Frölich in which a telephone is used, upon the disk of which is mounted a mirror that permits a beam of light to be reflected from it. Any vibration of the disk gives an angular motion to the ray of light, and this motion is in turn recorded upon a moving photographic plate. Other examples might be mentioned in illustration of this method—for instance, a wire which is deflected in a magnetic field or stream of mercury so influenced; but it will be noticed that in all of these cases an appreciable amount of *ponderable* matter is required to be moved backward and forward during each reversal of the current. When the current reverses hundreds of times per second the unavoidable difficulty is introduced that the forced oscillations of this ponderable matter, no matter how small in amount, become so superimposed

upon those of the current which it is desired to measure that they are inseparably mixed together; and the record does not show the true current, but the resultant vibrations of the instrument. That this is the case with the method of the telephone above referred to has been established beyond a doubt, it seems, by experiments conducted at Cornell University by Mr. Henry Floy. The current furnished to the telephone was carefully measured by the "method by points," and care was taken to see that the current as measured by points was the same as that used in the telephone. The vibrations of the telephone did not even approximately agree with the current as measured by well-established methods.

Bearing these points in mind, and remembering the high frequency of some of the oscillations which it is desired to record, may we not with some degree of certainty predict that any of these methods requiring the rapid motion of ponderable matter will be open to precisely the same objections which are noticed in the case of the telephone? Without answering this question, probably all will agree that the difficulty may *certainly* be avoided by using as a vibrator, instead of this so-called "*ponderable matter*," a vibrator that has *no* mass. It is to this question of finding a form of vibrator *without* mass that I invite your attention.

The Massless Vibrator.

The idea of the massless vibrator is perhaps already suggested in the beam of light. But how shall we cause a beam of light to have a change in direction simply by means of a current flowing in a circuit without the intervention of some moving material? A way of influencing a beam of light directly by an electric current (or more properly by its magnetic field) is that discovered long ago by Faraday. It is by means of the discovery of the rotation of the plane of polarization by an electric current that I propose a method of obtaining a massless vibrator. The

explanation will be made clearer by reference to the diagram of apparatus (Fig. 70). A beam of light is passed through a polarizer (Nicol prism), so that the vibrations of the beam take place in only one plane upon emergency. If it is then passed directly through an analyzer (Nicol prism) the latter may be set at such an angle as to prevent all light from passing through it, and thus produce darkness beyond the analyzer. Faraday's discovery was,

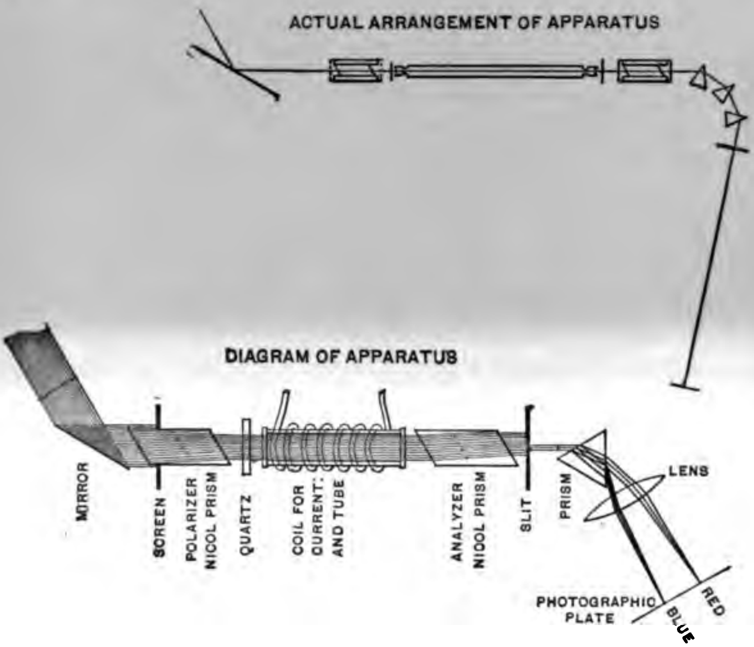


FIG. 70.

that if a beam of polarized light is passed through some *substance* in the direction of the lines of magnetization within that substance, there is a rotation of the plane of polarization in a direction which is the same as the direction of the current required to produce such a magnetic field. The direction of rotation is unaltered, therefore, whether the light beam advances in the same or the opposite direction to the magnetization, so that a

beam reflected back and forth through the substance several times has its rotation increased by equal amounts each time. If the direction of the ray of light is at right angles to the line of magnetization there is no rotation produced. The amount of this rotation has been carefully investigated by Verdet, who announced laws by which it may be expressed. They are summed up in the following statement: "The rotation of the plane of polarization for monochromatic light is in any given substance proportional to the difference in magnetic potential between the points of entrance and emergence of the ray"; that is, it is equal to a constant times this difference of potential, and is expressed by the formula

$$(1) \qquad \theta = vV,$$

where θ = angle of rotation, V = difference in magnetic potential, and v for a given wave-length is constant in any one substance. This constant is known as Verdet's constant. If now the light is passed through the polarizer and then through a tube containing the substance used, around which is wound a coil of wire, and thence through the analyzer, an observer would find complete darkness upon looking through the analyzer, when set in the crossed position. But if without moving the analyzer a current is sent through the coil on the tube, light appears to the observer. This is because the plane of polarization has been rotated by the current, and practically the prisms are no longer crossed. Now let the analyzer be rotated while the current is still flowing, and the observer will see a series of beautiful colors through the analyzer, a different one for each position of it; but as long as the current flows, he cannot produce darkness again by any amount of rotation of the analyzer.

The effect suggests what is known to be a fact, that the different wave-lengths composing white light are rotated by the current in different amounts, so that when the analyzer is turned to the angle corresponding to the yellow light, say, only the yel-

low light is prevented from passing through the analyzer. All the other rays, being rotated by different amounts, pass through the analyzer, and there being mixed together they give rise to the series of beautiful complex colors above mentioned. A different color is seen for each position of the analyzer, because in each position a different color is subtracted from white light, and the observer sees what is left, or merely the complementary color.

The law which tells the amount of rotation given to the different colors is pretty accurately known; and theory in this case is in close accord with the observed facts. The equation which closely expresses the amount of the dispersion for the different wave-lengths may be written

$$(2) \qquad v = \frac{cn^2}{\lambda^2}\left(1 - \frac{\lambda}{n}\frac{dn}{d\lambda}\right),$$

where v is the so-called Verdet's constant, λ the wave-length, and n the index of refraction of the medium; c is a constant for any one medium, which is however for different media inversely proportional to the permeability of the medium. This is a formula at which Maxwell arrived from his theory of molecular vortices, and we shall see how closely it is in accord with observation. We see by this formula that Verdet's constant depends not only upon the wave-length, but upon the index of refraction corresponding to that particular wave-length, and also upon the rate of change of the index with respect to the wave-length. If this rate of change of n with respect to λ is small, as would be the case with a substance where the dispersion is small, and the index of refraction regarded as approximately constant, then it is seen that the formula reduces to an extremely simple form, viz.,

$$(3) \qquad v = \frac{c_1}{\lambda^2}.$$

Here Verdet's constant is inversely proportional to the square of

the wave-length. Using this approximate form for the present, we see from Verdet's law, equation (1), that

$$(4) \qquad \theta = vV = c_1 \frac{V}{\lambda^2}.$$

But the difference of magnetic potential, V, is $\frac{4\pi Si}{10}$, where Si is ampere-turns, and thus we have

$$(5) \qquad \theta = 4\pi c_1 Si/10\lambda^2 = c_2 i/\lambda^2,$$

where

$$(6) \qquad c_2 = 4\pi c_1 S/10.$$

A reference to Fig. 71 will show this relation between angle of rotation, wave-length, and current. Several spirals are shown, corresponding to the several lines of the spectrum, known as A, B, D, F, and G. The radii of the circles which intersect these spirals are proportional to the current flowing in the circuit, while the angle which the radius, drawn to any point of intersection, makes with OP represents the rotation for that particular wave-length and current. The spiral OA is in the extreme red, and OG in the violet of the spectrum, and the diagram thus indicates that the red rays are not rotated so much as the blue. The direction of rotation in the diagram is as indicated by the arrow. Now, returning to the observer looking through the analyzer, if he could resolve the light there seen into the pure colors of the spectrum, what he should expect would be, with no current, a complete spectrum, since *all* rays are rotated by the current. But let him rotate the analyzer, and he finds that first one color and then another disappears, and a *dark band* is seen to move across the spectrum as he rotates the analyzer. Again, let him rotate the analyzer to a certain angle and leave it there while he varies the current. He should expect that the band would move, and vanish entirely with zero current, and thus prevent observation for small currents.

Fortunately we have substances which naturally rotate a beam of polarized light, for by means of this aid we may obviate the difficulty that the band vanishes with no current. For instance, a parallel plate cut from a crystal of quartz perpendicu-

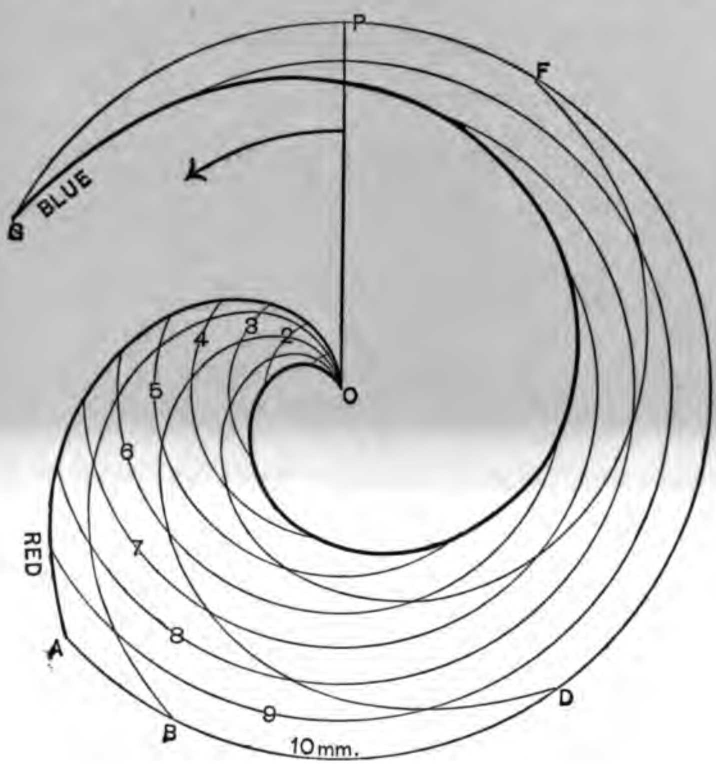


FIG. 71.

lar to the optic axis has this property of rotating the plane of polarization. Quartz is selected for the material used because of its great transparency and high specific rotatory power. The law of the rotation is similar to that already mentioned for the rotation by the current. The approximate law is, that the ro-

tation is inversely as the square of the wave-length, which may be expressed

$$\phi = c_3 e/\lambda_2, \tag{7}$$

where ϕ is the angle of rotation for the wave-length λ, c_3 is a constant, and e is the thickness of the plate. The thickness of the quartz plate is seen to correspond to the current in equation (5). Fig. 71 represents the actual rotation for different thicknesses of quartz, each circle corresponding to a plate one millimeter thick. The equivalent of a quartz plate one millimeter thick is represented approximately by 35,700 ampere-turns wound upon a tube containing carbon bisulphide. This latter is the substance used, being selected on account of its high transparency and specific rotation.

If a quartz plate be placed between polarizer and analyzer, the effect is the same as if the current circulated around the tube of carbon bisulphide, and we may, by rotating the analyzer, move the dark band completely across the spectrum by means of the quartz plate without any current. But suppose we set the analyzer so that the dark band remains in the centre of the spectrum and then pass a current through the coil. We observe a motion of this dark band back and forth through the spectrum as the current is repeatedly reversed. For any given current its position is always the same, so that its motion may be calibrated by passing known currents through the coil. Have we not in this found a weightless vibrator that is sure to move in unison with the current?

Before passing on to the more practical side of the question, it may be asked, will this band move back and forth so that its displacement is approximately proportional to the current? The answer to this question lies so near at hand that your attention is invited to it for a moment. The rotation of the plane by quartz is approximately represented by the formula

$$\phi = c_2 e/\lambda^2.$$

The rotation by the current is represented by

$$\theta = c_2 i/\lambda^2.$$

If both these rotations take place together, the resultant is merely the sum of the components, and

(8) $$\chi = \phi + \theta = (c_1 e + c_2 i)\frac{1}{\lambda^2}.$$

The position of the dark band depends upon the position of the analyzer. Let the analyzer be set at some convenient angle a, with the position of complete darkness, and let it remain there. Then the wave-length or color where the dark band occurs for the quartz plate (being called λ_0) is given by (7) above, and we have

(9) $$a = c_1 \frac{e}{\lambda_0^2}.$$

The wave-length corresponding to this constant angle a, when both quartz and current are used, is given by (8), and we have

(10) $$a = (c_1 e + c_2 i)\frac{1}{\lambda^2},$$

in which λ is that wave-length corresponding to a certain current i, and therefore i and λ are co-ordinate variables. Equating the values of a, we have

(11) $$\frac{c_1 e}{\lambda_0^2} = \frac{c_1 e + c_2 i}{\lambda^2}.$$

This may be written

(12) $$\lambda^2 = \frac{c_2 \lambda_0^2}{c_1 e} i + \lambda_0^2,$$

and in this form the relation between wave-length and current is seen to be represented by a parabola. In Fig. 72 are represented two sets of parabolas obtained from equation (12) by as-

suming that λ_0 and e take in succession different values. When $e = 2$ mms. the set of parabolas marked I is obtained, and where $e = 6$ mms. set II is obtained. By giving λ different values we merely vary the parameter of the parabola without changing the origin. It will be remembered that λ_0 represents that wave-length corresponding to the positions of the dark

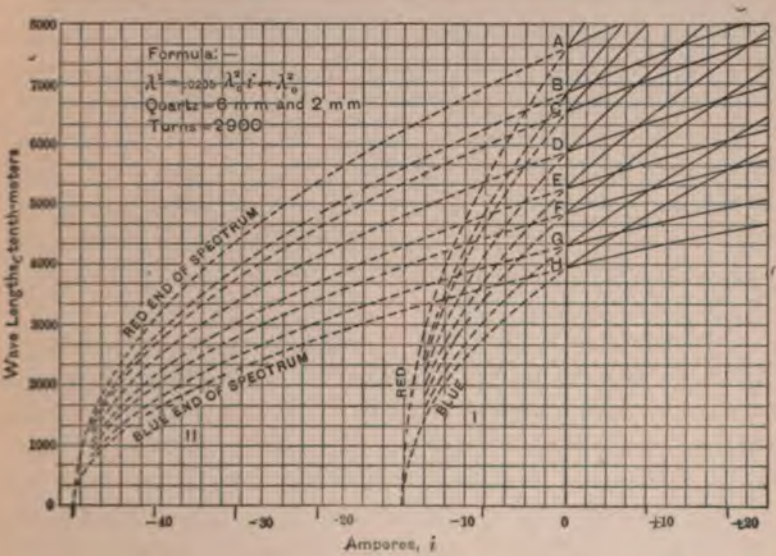


FIG. 72.

band for no current. It is therefore the value of λ when i is equal to zero, as appears from the equation independently. The axis of λ is the vertical line to the right of the figure, upon which the letters A, B, etc., are written. These letters show the positions of the various Fraunhofer lines, and one parabola is drawn for each line. Each parabola then corresponds to one setting of the analyzer, and the dark band is found at these lines of the spectrum for zero current. The upper parabola is at the red end, and the lower at the blue end, of the spectrum. The axis of current is the base line of the diagram, and currents to the left of the vertical line are called negative, while those to the

right are called positive. The axes of all the parabolas coincide with each other and with that of the current, and for a given quartz plate they all intersect this axis at the same point, so that taking different settings of the polarizer is equivalent to changing the parameter only of the parabola.

The interpretation of these results may be put as follows: If we have a spectrum in which the wave-lengths are proportional to the distances along the spectrum (which is the case with Professor Rowland's arrangement of a concave grating), then the displacement of the dark band to one side or the other, due to the current, will be exactly according to the shape of these parabolas near the zero point; that is, near the vertical line lettered A, B, etc. Since it appears that each parabola at such a great distance from the origin is nearly a straight line, the displacement in such a spectrum will be nearly proportional to the current.

A noticeable feature, easily revealed by the graphical construction, is that in the red end of the spectrum, where the inclination of the parabola to the x axis is the greatest, the motion of the band will be the greatest for a given current. It is understood that this construction has to do with the relation between the wave-length and the current, and not between the displacement and current, unless the wave-length and displacement are proportional. It does not apply, for instance, to the displacement in the spectrum of most prisms. In the prisms used the red rays were so crowded together that the motion as observed was nearly the same in the red as in the blue. The width of the band, however, is for this reason narrower in the red than in the blue—a consideration of considerable practical importance.

Description of Some of the Apparatus.

The tube upon which the coil carrying the current was wound was a glass tube 1.4 cms. internal, and 1.8 cms. ex-

ternal, diameter, and 70.15 cms. long. The tube was filled with carbon bisulphide, which was confined in the tube by means of two plane parallel plates of glass, each 1.3 mms. thick, fitted tightly upon the ground ends of the tube. Upon this tube was wound six layers of No. 18 double cotton copper magnet wire, occupying a length on the tube of 61.5 cms. The wire was wound so that 100 turns occupied 12.7 cms. Thus the total number of turns, 2900, is very large, considering the size of wire.

The light used was sunlight reflected from the mirror of the heliostat.

The Nicol prisms are two fine specimens which were obtained by Dartmouth College at a time when larger specimens could be obtained than may now easily be found. The slit does not need to be very narrow. A width of a quarter to a half millimeter will do better than a narrower one, because more light is admitted to the photographic plate, and in passing through so many different substances even sunlight is rendered comparatively feeble by the time it strikes the photographic plate.

A further description of the apparatus is hardly deemed to be necessary, inasmuch as no claim is made to having obtained more than the most crude of first results, which may be the results obtained by apparatus arranged in a comparatively poor manner for the end sought. Yet the results obtained seem to be so promising for the future that the subject is presented to you at this early date in the experiment in the hope that it may soon receive an impetus from other experimenters who have better facilities than those at my disposal, and thus become a fruitful source of extending our knowledge of instantaneous current flow in conductors.

The objections which most naturally suggest themselves against this method of taking current curves are perhaps the following. The photographic plate must move so quickly that the time of exposure of any one part of the plate is extremely short. To meet this demand the most sensitive plates that can

be made should be used. The width of the band with any given plate depends largely upon the time of exposure. Then, too, a plate is to be desired that will photograph toward the red end of the spectrum as well as in the blue. The band does not possess very sharp outlines, but gradually shades off from dark to light.

These objections do not have so much weight, however, in cases where the general direction of the variation of the current is what is wanted, more than any exact measurement of its amount, and in the majority of cases this is really what is required, yet it cannot be said that in these preliminary experiments the band used was nearly as sharp as may be obtained.

Another objection of a different nature that seems difficult to avoid is the fact that the coil, which is wound upon the tube, must necessarily possess a small amount of self-induction. It may be said, however, that even though we are prohibited from measuring certain currents on account of this self-induction we are always sure that we are measuring the exact current which is flowing through the coil.

A More Exact Expression of the Relation between the Wave-length and Verdet's Constant.

The approximate relation between the wave-length and Verdet's constant used above was that Verdet's constant varied inversely as the square of the wave-length. It is considered of sufficient interest to inquire just how nearly this is an approximate formula.

By reference to equation (2) it is evident that if we only knew the relation between the index of refraction and the wave-length we might obtain the relation between the wave-length and Verdet's constant in terms of these two quantities alone and constants.

Such a relation is afforded by Briot's formula, which is a

modification and improvement upon the well-known formula of Cauchy. This is

$$(14) \qquad 1/n^2 = k\lambda^2 + A + B/\lambda^2 + C/\lambda^4 + \ldots,$$

where n is the index of refraction corresponding to the wave-length λ, and k, A, B, etc., are constants for the given substance. Assuming that all terms beyond B/λ^2 are negligible, we may differentiate with respect to λ and obtain the equation

$$(15) \qquad \frac{\lambda}{n}\frac{dn}{d\lambda} = n^2\left(\frac{B}{\lambda^2} - k\lambda^2\right).$$

Upon eliminating B/λ^2 between (14) and (15) we obtain

$$(16) \qquad \frac{\lambda}{n}\frac{dn}{d\lambda} = 1 - 2kn^2\lambda^2 - An^2$$

Substituting in (2) the expression thus obtained, we have

$$(17) \qquad v = cn^5(2k + A/\lambda^2).$$

But by (14)

$$(18) \qquad n^5 = (k\lambda^2 + A + B/\lambda^2)^{-\frac{5}{2}}.$$

Hence

$$(19) \qquad v = c(2k + A/\lambda^2)(k\lambda^2 + A + B/\lambda^2)^{-\frac{5}{2}}.$$

This formula represents to a high degree of accuracy the observed values of Verdet's constant for carbon bisulphide. It probably would for any other substances, but carbon bisulphide is the only one to which it has been applied by me. The constants k, A, and B may be found by means of equation (14) and the observed values of the refractive index for known wave-lengths. The values used are those observed by Messrs. Gladstone and Dale. (See Glazebrook's Physical Optics, page 243.)

Line of Spectrum.	Index of Refraction for Carbon Bisulphide.	Line of Spectrum.	Index of Refraction for Carbon Bisulphide.
A 7621	1.6142	E 5270	1.6465
B 6870	1.6207	F 4861	1 6584
C 6563	1.6240	G 4308	1.6836
D 5893	1.6333	H 3969	1.7090

These values give curve I, in Fig. 73. The lines A, F, and

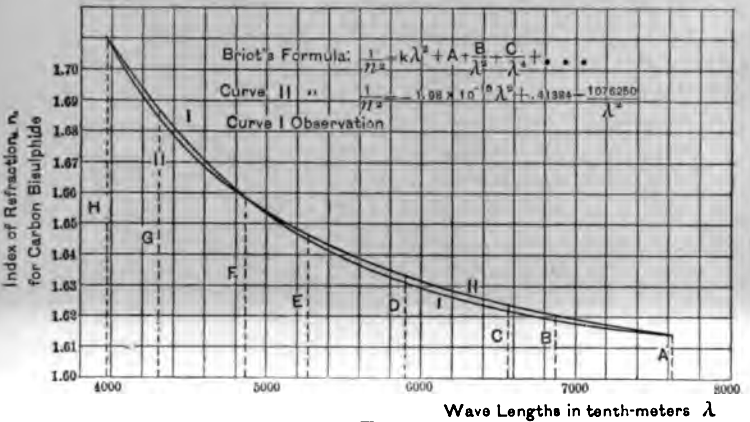


FIG. 73.

H were selected and three simultaneous equations formed from (14), so that the resulting curve II should pass through these three observed points.

The values

(20) $k = 1.98 \times 10^{-10}$,

(21) $A = .41384$,

(22) $B = 1076250$.

were obtained by the determinant solution of these three simultaneous equations. The resulting curve I may not appear to coincide very closely with curve II, but it must be remembered that the origin of coördinates is a long distance below the paper, and the apparent differences are but a very small fraction of the whole. The unit is the tenth meter for wave-lengths.

Having these constants, they may now be substituted in

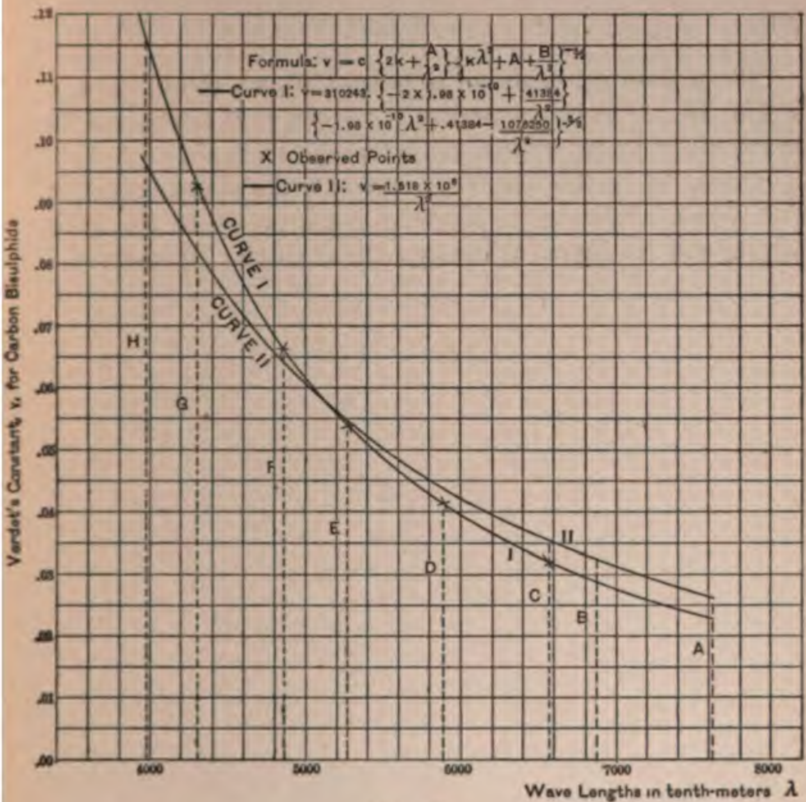


FIG. 74.

(19), and c determined from the observed values of Verdet's constant. These observed values are:

Line of Spectrum. (λ)	Verdet's Constant for Carbon Bisulphide. (v)
C 6563	0.0319′
D 5893	0.0415′
E 5270	0.0537′
F 4861	0.0667′
G 4308	0.0920′

The constant thus determined, where a minute is the unit of angle, gives

(23) $$c = 310243.$$

Using these constants for equation (19), we obtain curve I, in Fig. 74. The points marked $\times$ are observed values, and the calculated curve practically passes through them all.

Curve II in this diagram represents the approximate law that Verdet's constant is inversely as the square of the wave-length, and the degree of the approximation may be observed.

FIGURE I.

FIGURE 17.—*Negative* 18.

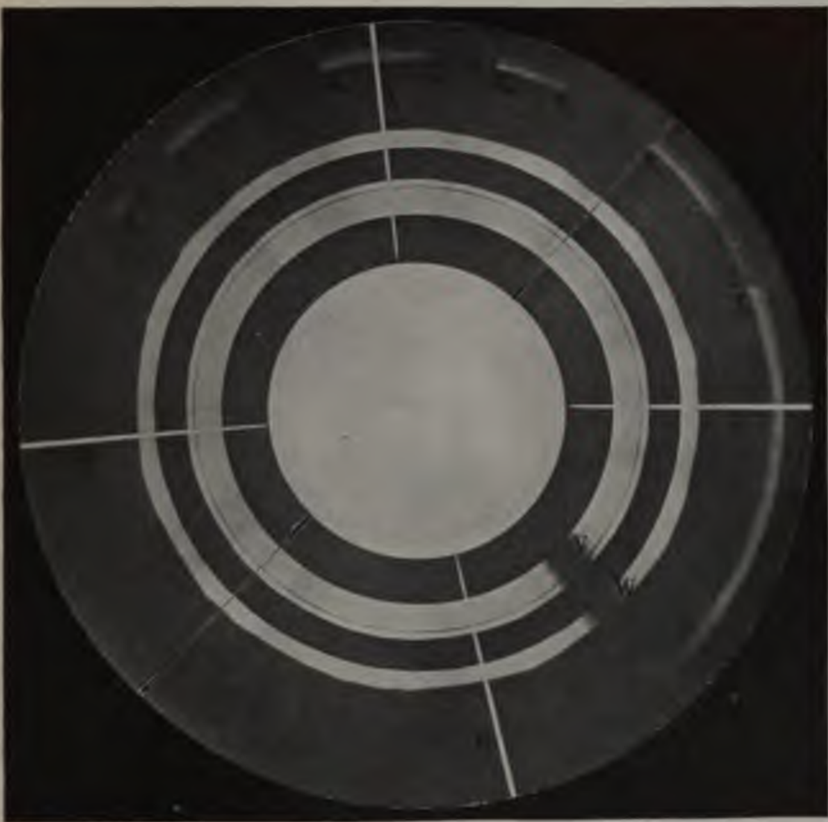


FIGURE 18.—*Negative* 19.

FIGURE 6.—*Camera, front view.*

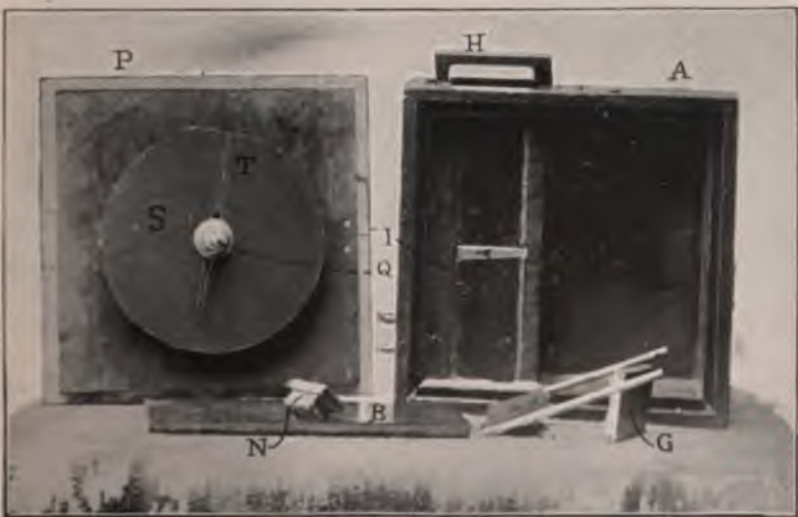


FIGURE 7.—*Camera, interior view.*

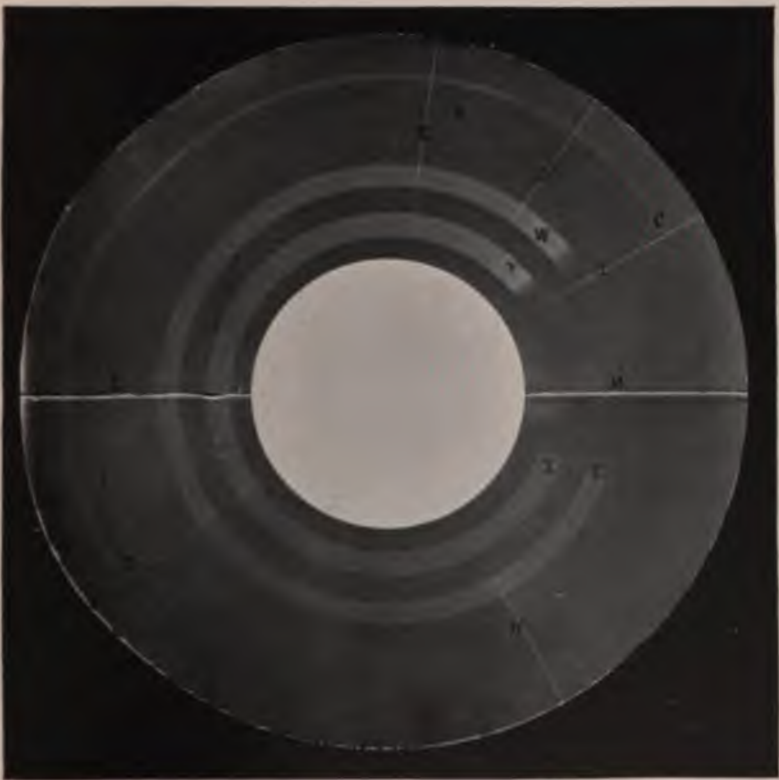


FIGURE 10.—*Negative* 8.

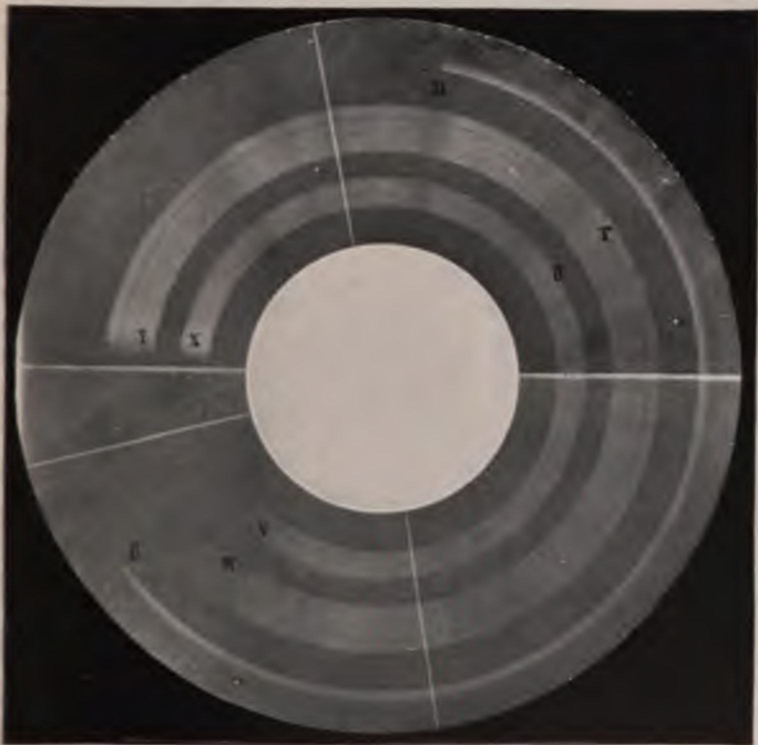


FIGURE 11.—*Negative* 13.

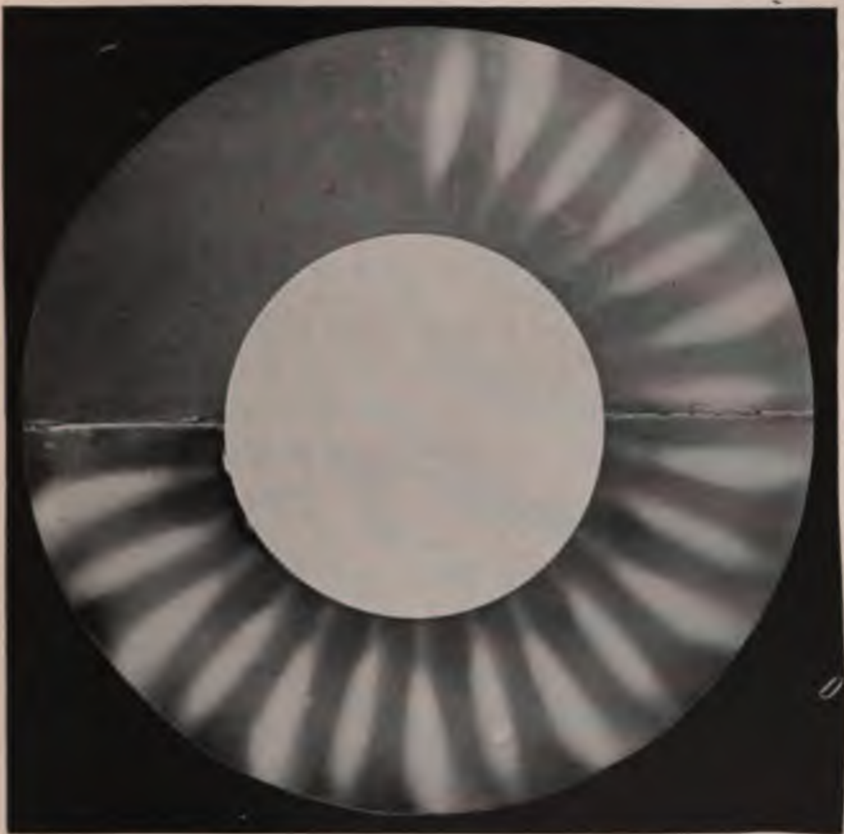


FIGURE 12.—Alternating current arc light.

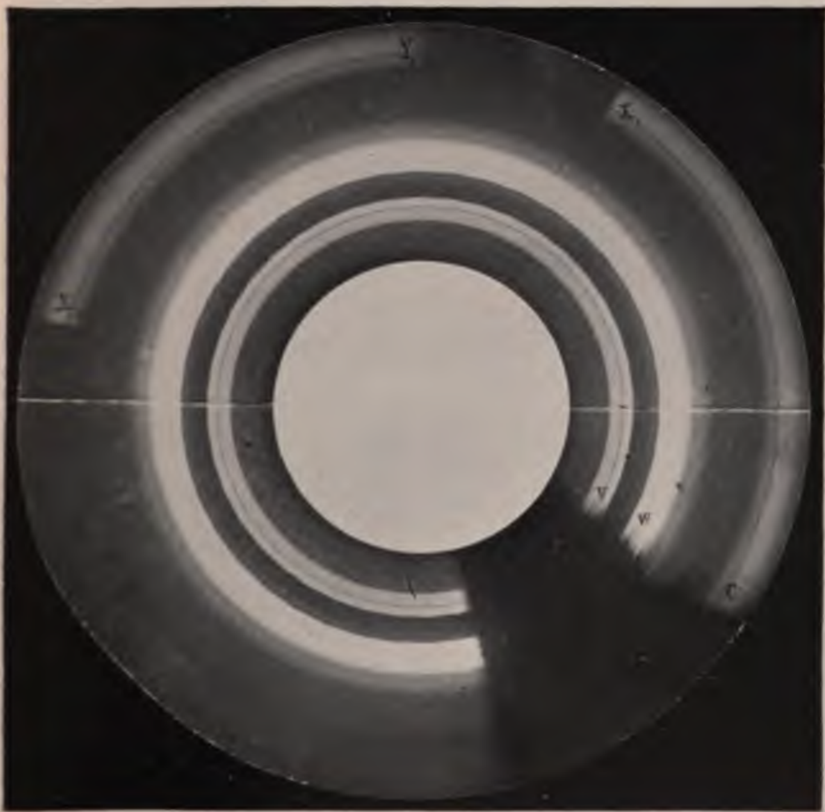


FIGURE 14.—*Negative* 10.

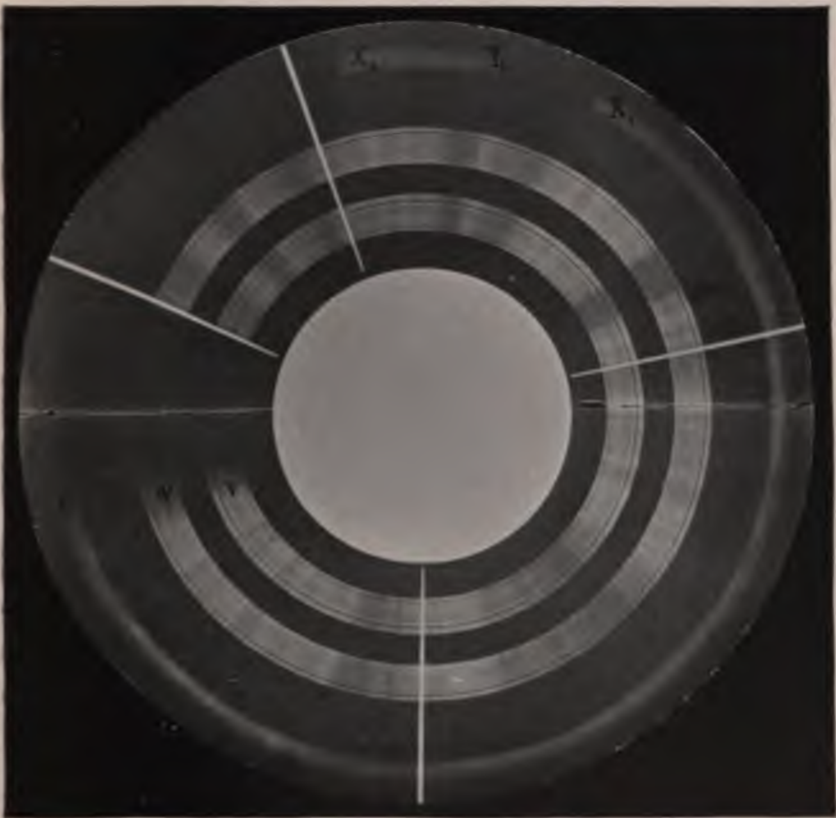


FIGURE 15.—*Negative* 16.

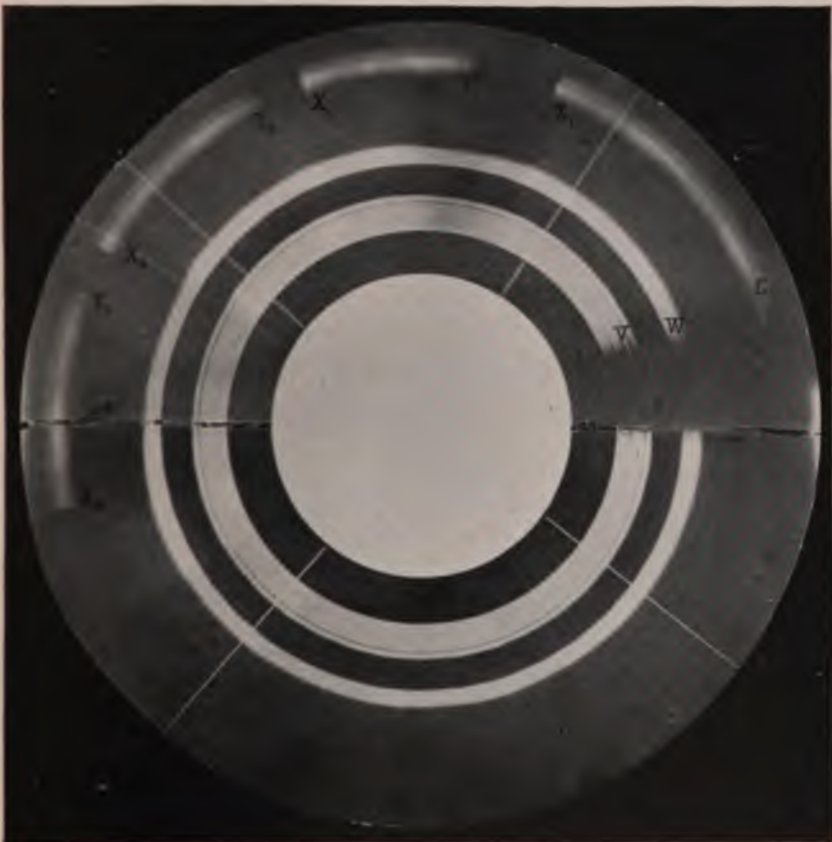


FIGURE 16.—*Negative* 17.

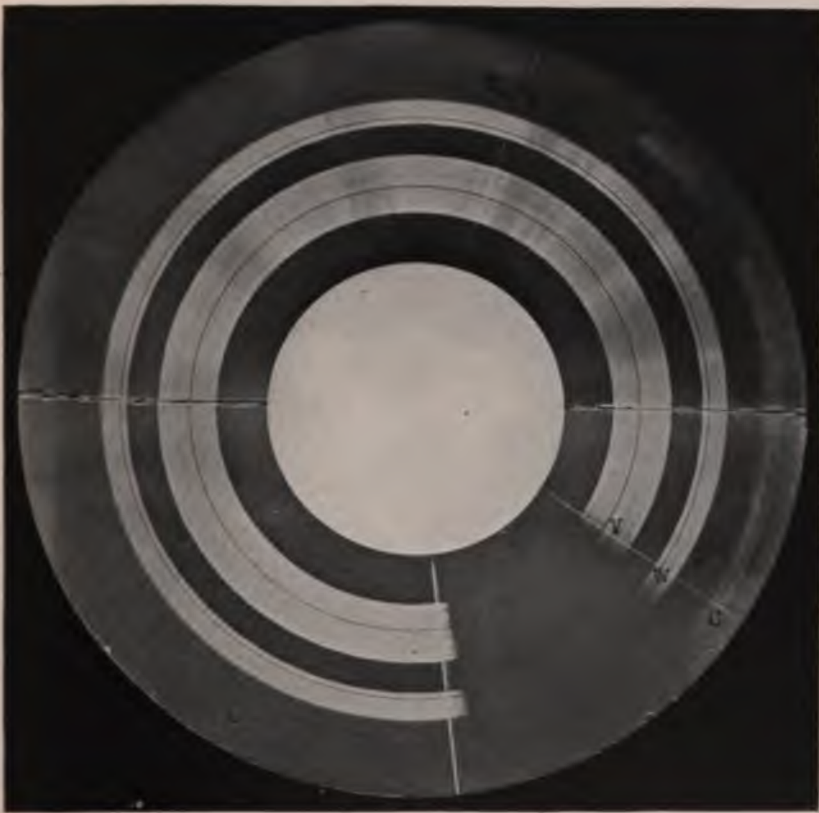


FIGURE 17.—*Negative* 18.

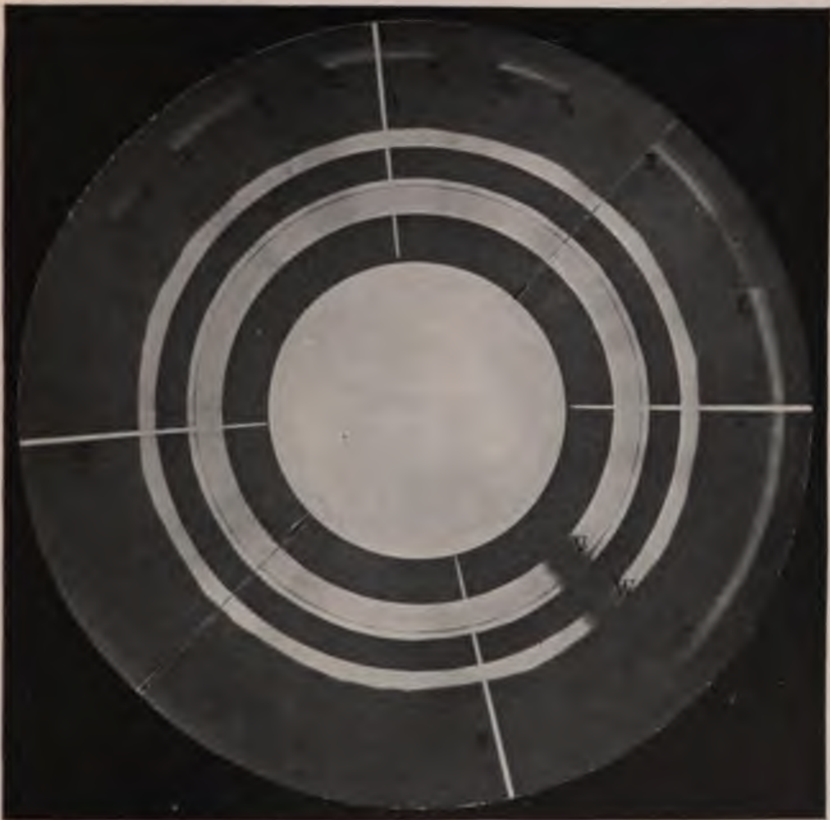


FIGURE 18.—*Negative* 19.

FIGURE 19.—*Negative* 20.

FIGURE 29.
Tuning fork, 512 (single) vibrations per second.

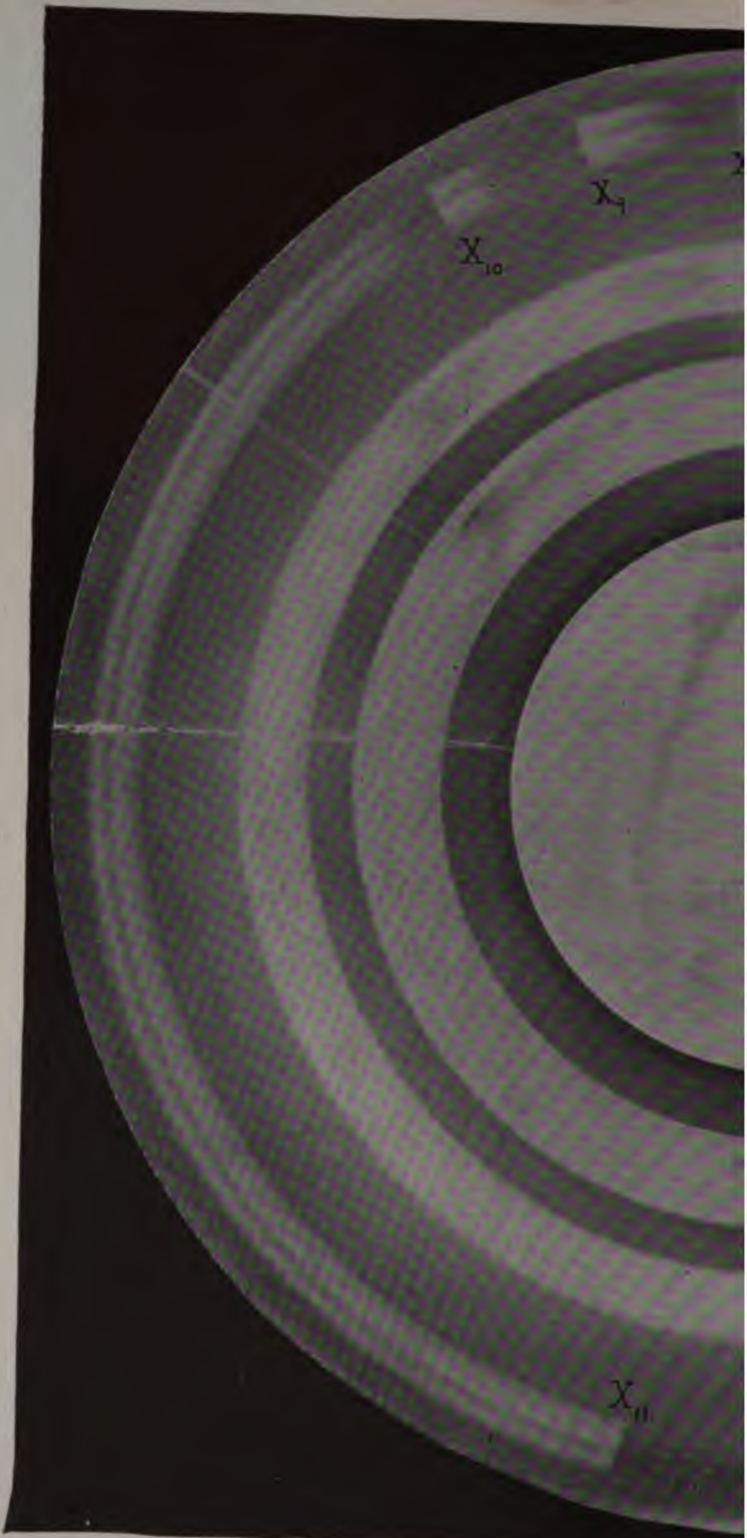


FIGURE 27

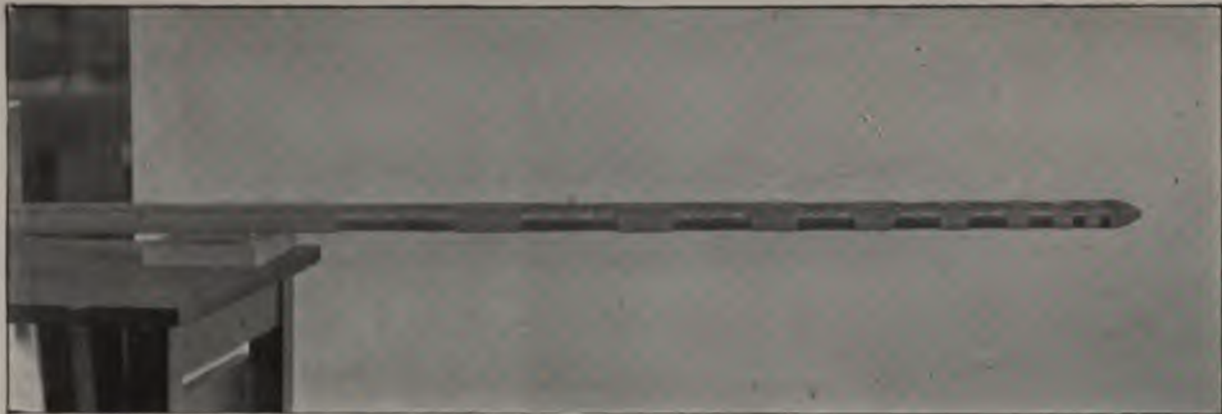


FIGURE 31.

FIGURE 27.

Tuning fork, 1024 (single) vibrations per second.

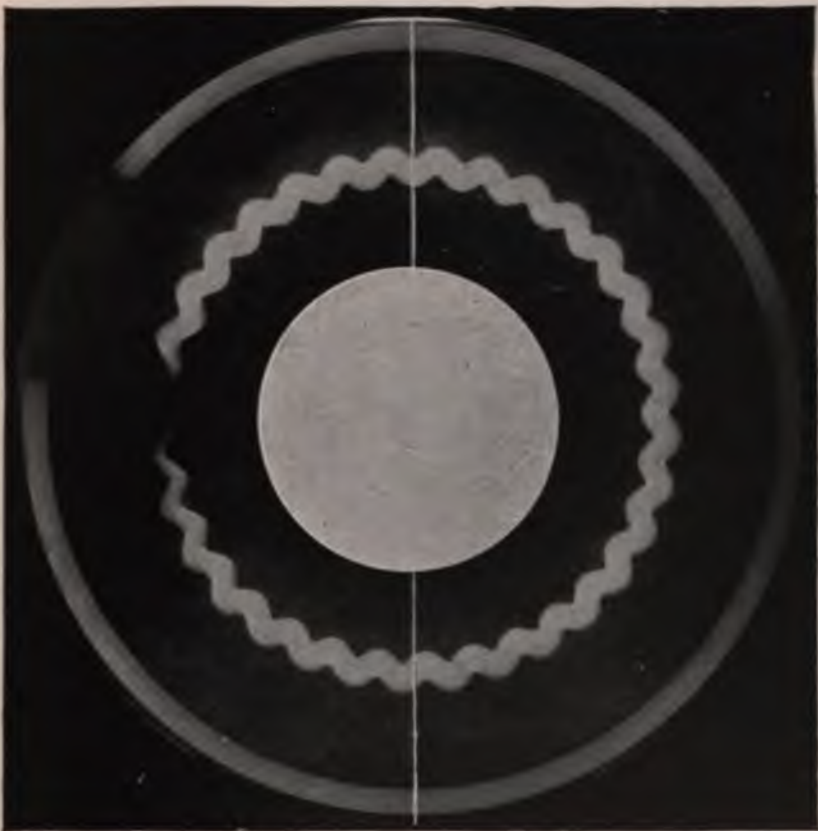


FIGURE 28.

Tuning fork, 512 (single) vibrations per second.

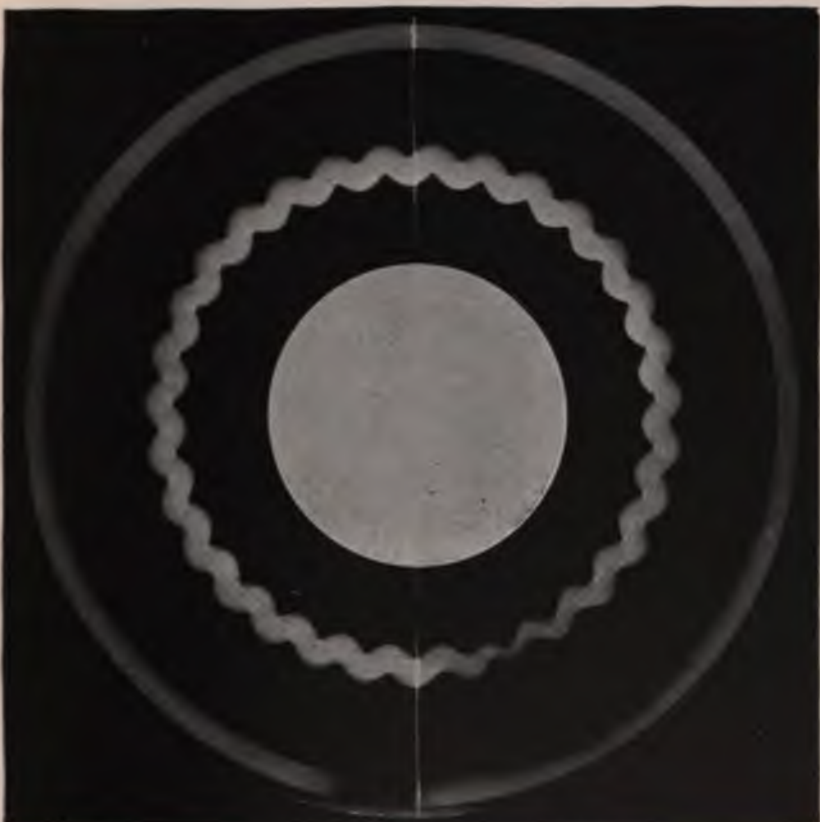


FIGURE 29.
Tuning fork, 512 (single) vibrations per second.

FIGURE 30.

FIGURE 31.

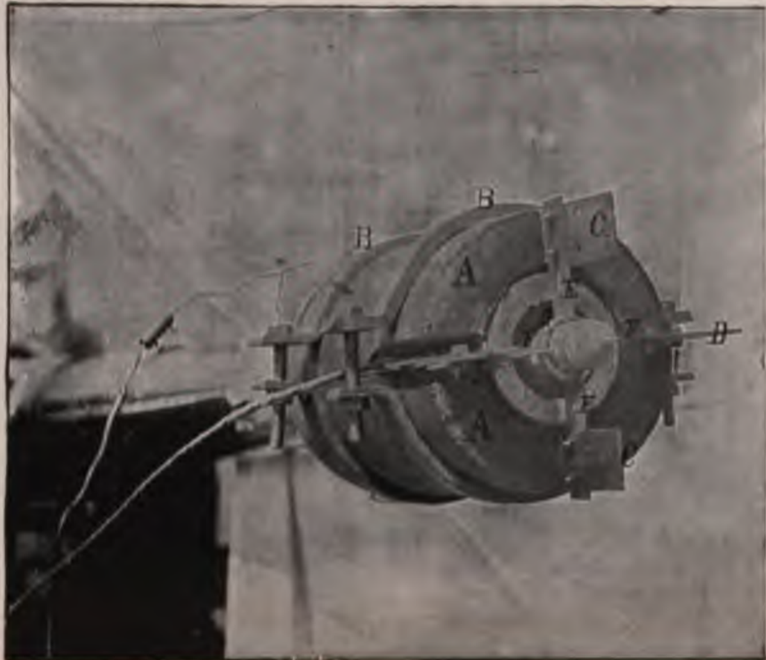
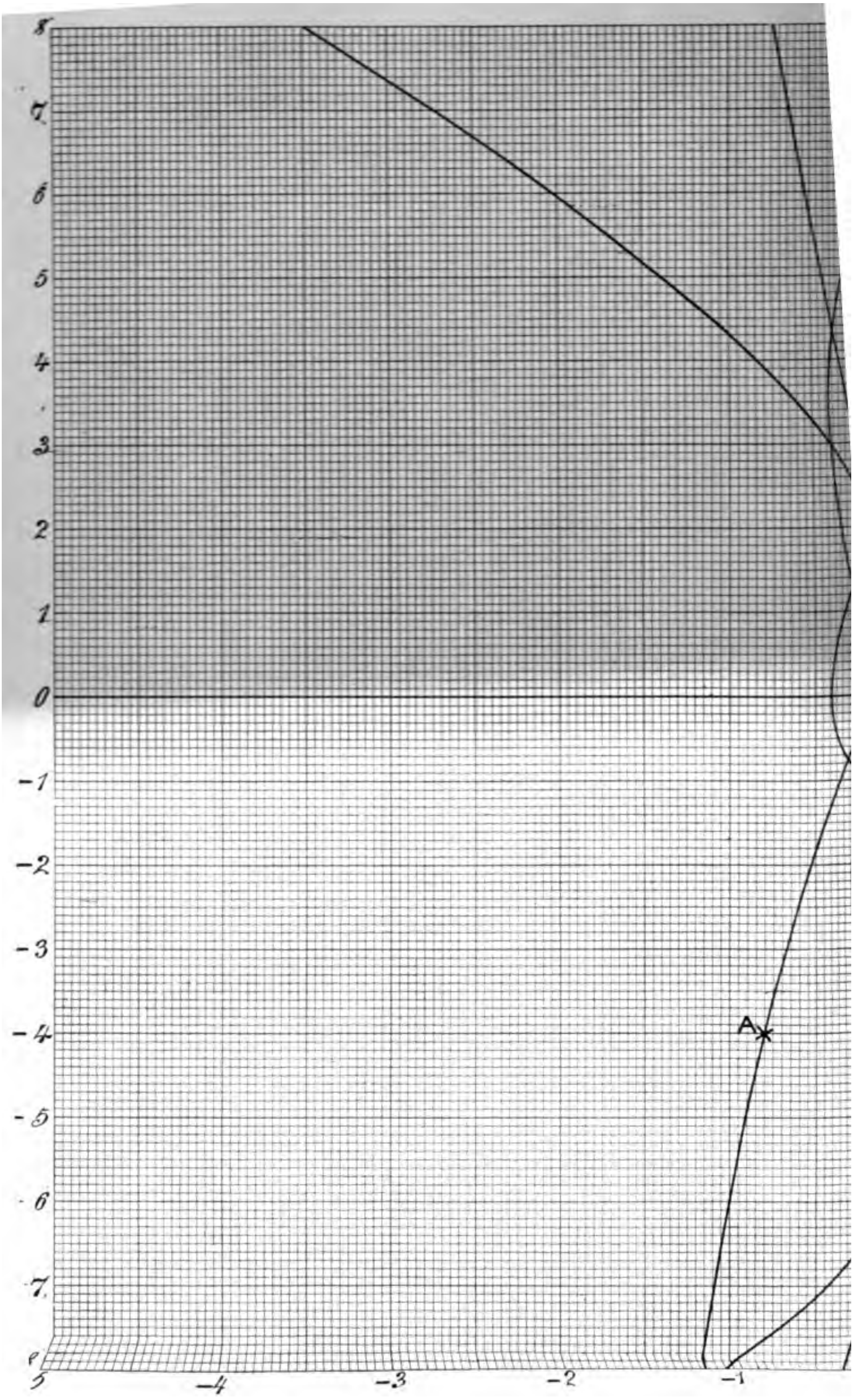
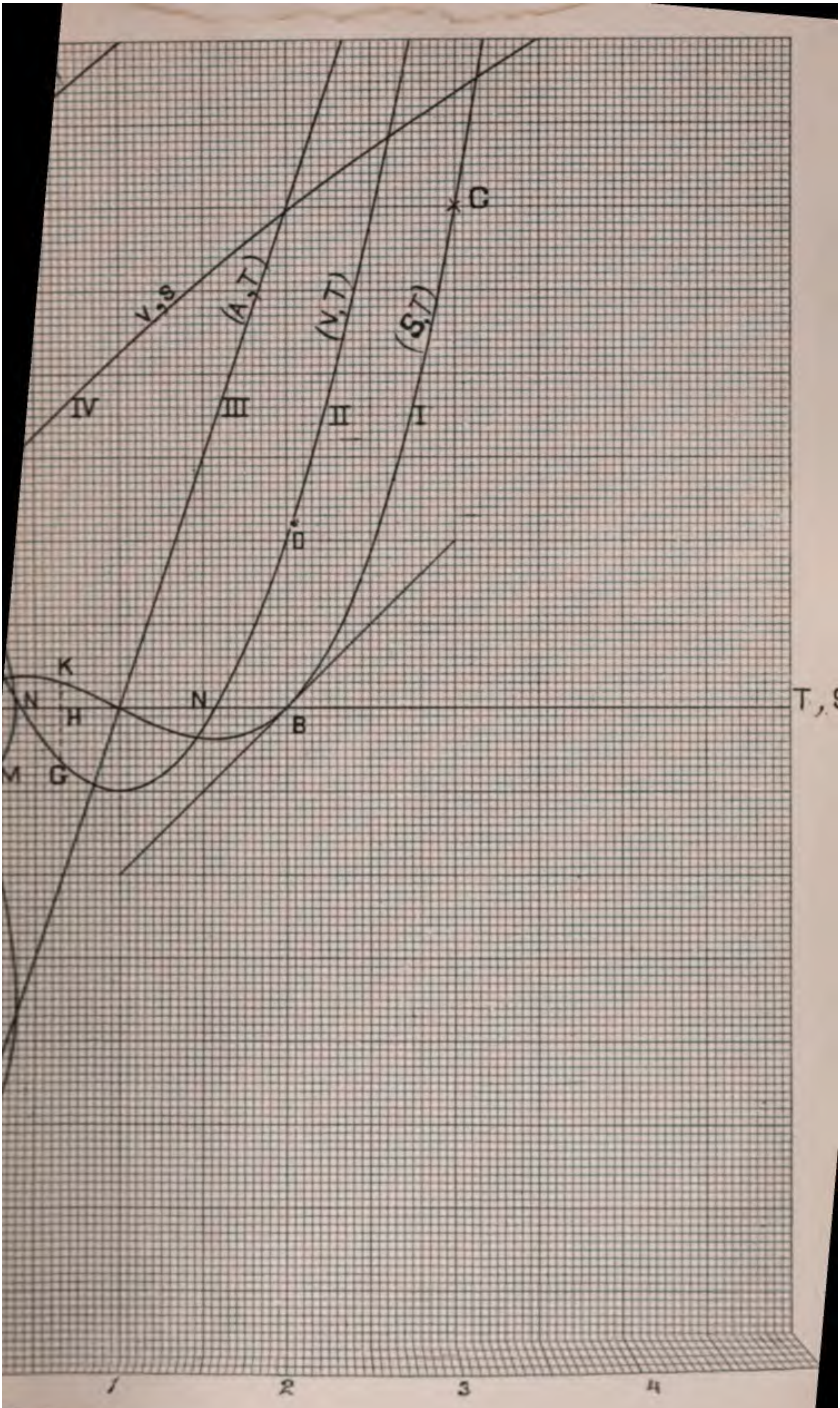


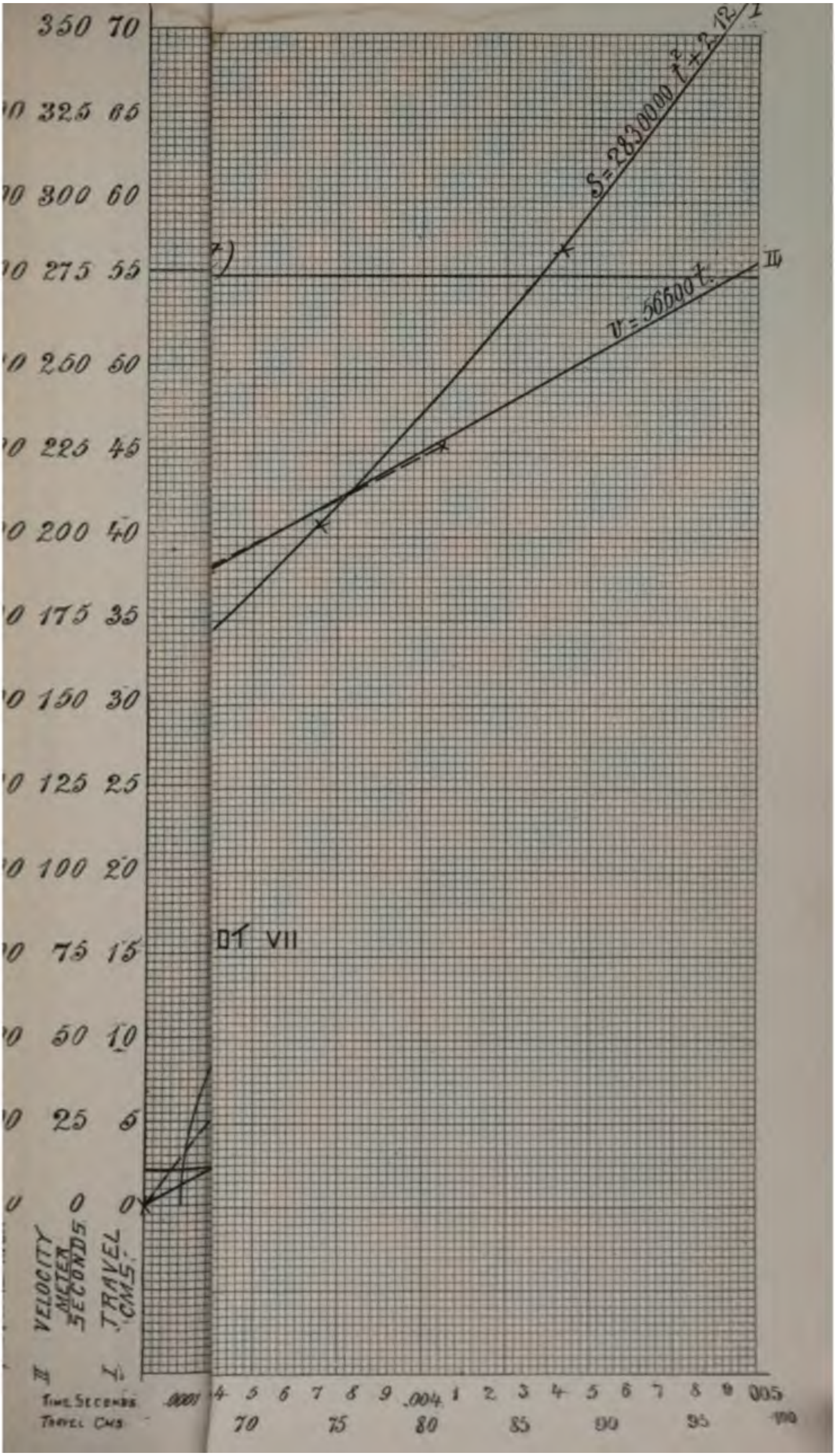
FIGURE 32.

FIGURE 33.

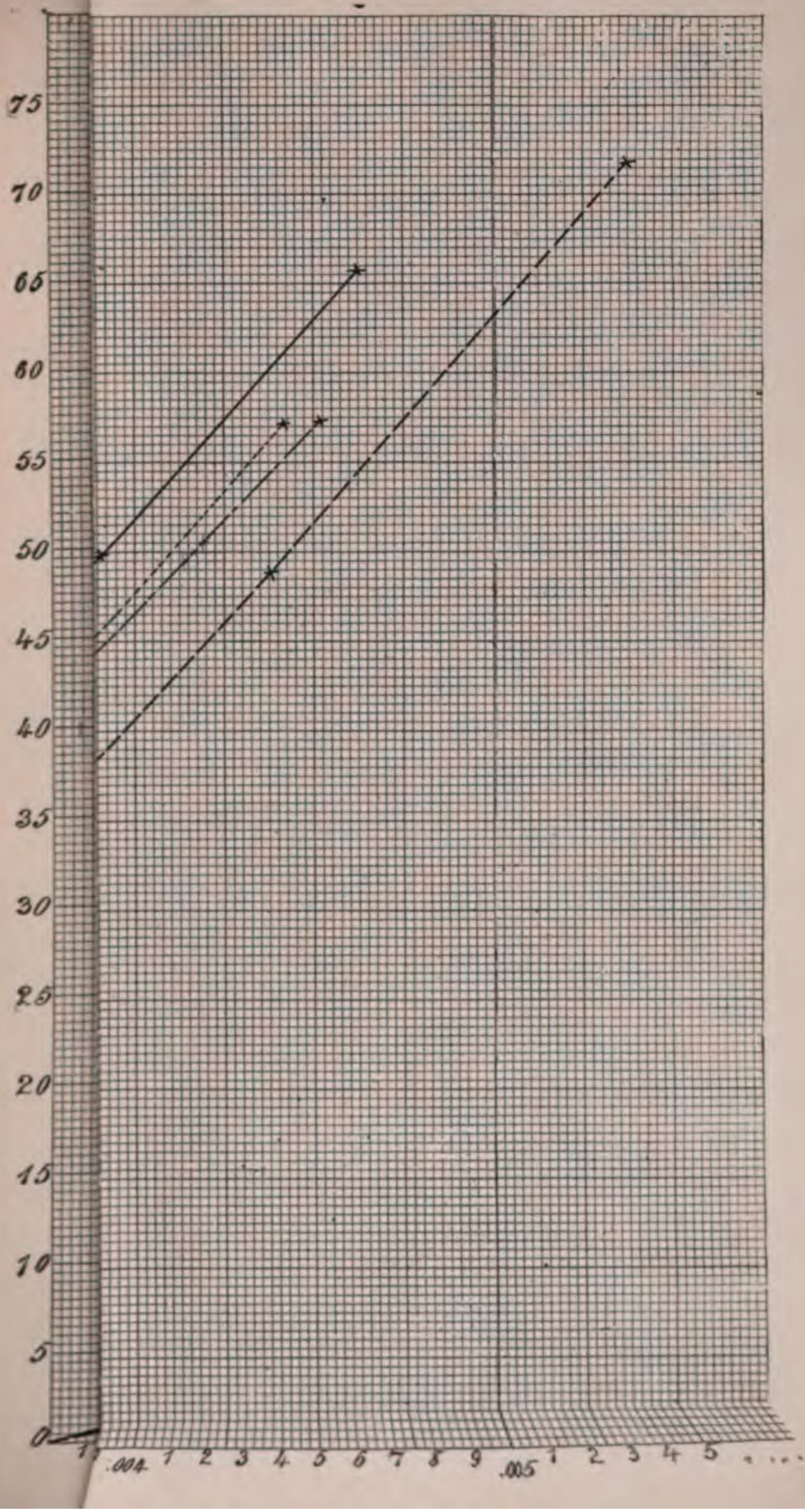


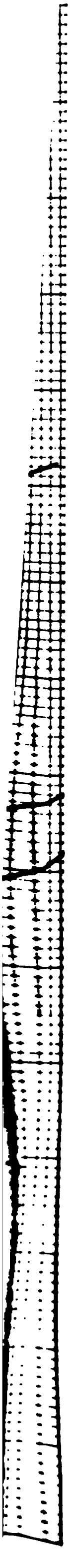
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-5
-4
-3
-2
-1
A


V, S
(A, T)
(V, T)
(S, T)
C
IV
III
II
I
D
K
N
N
H
B
M
G
T, S
1
2
3
4



$S = 2830000\,t^2 + 2.12$ I
$v = 566000\,t$ II
DT VII
350 325 300 275 250 225 200 175 150 125 100 75 50 25 0
70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
II VELOCITY METER SECONDS
I TRAVEL CMS.
TIME SECONDS .0001 4 5 6 7 8 9 .004 1 2 3 4 5 6 7 8 9 .005
TRAVEL CMS 70 75 80 85 90 95 100


75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
.004 1 2 3 4 5 6 7 8 9 .005 1 2 3 4 5



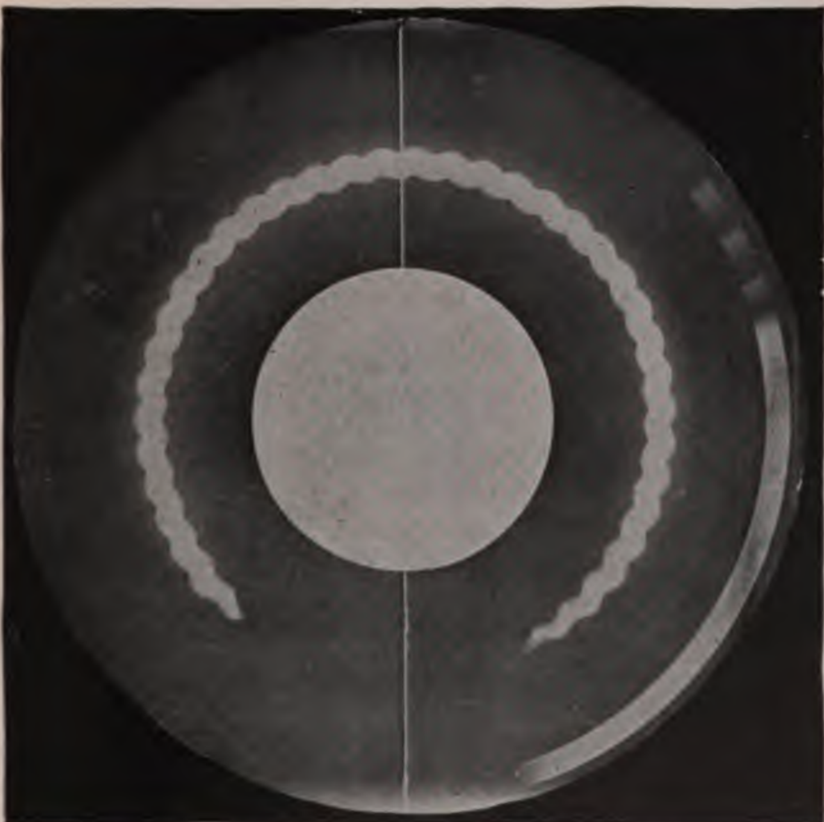


FIGURE 40.

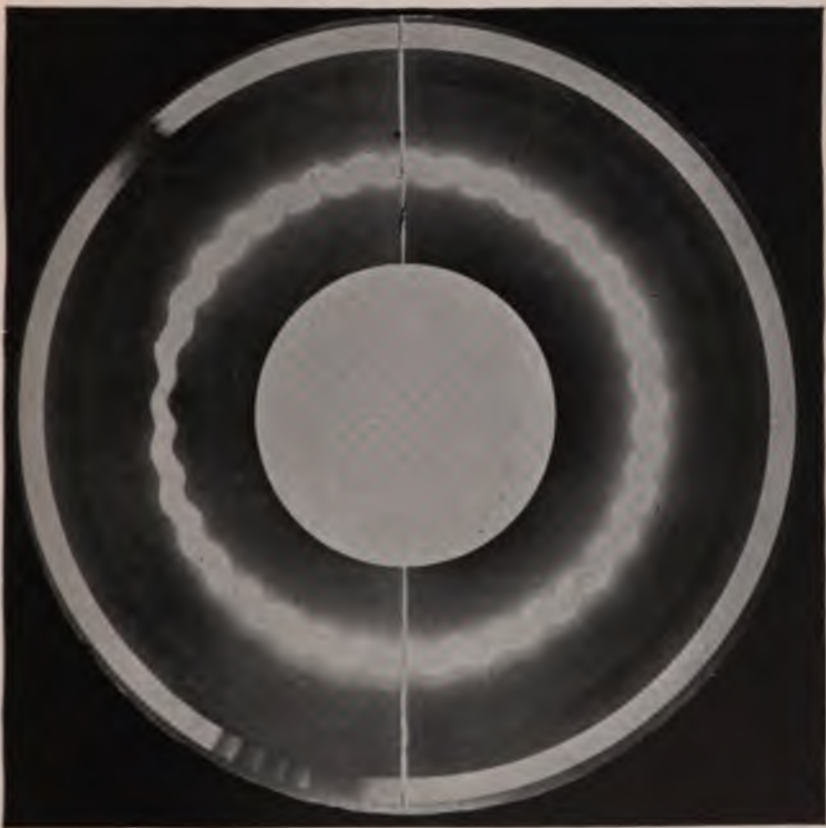


Figure 41.

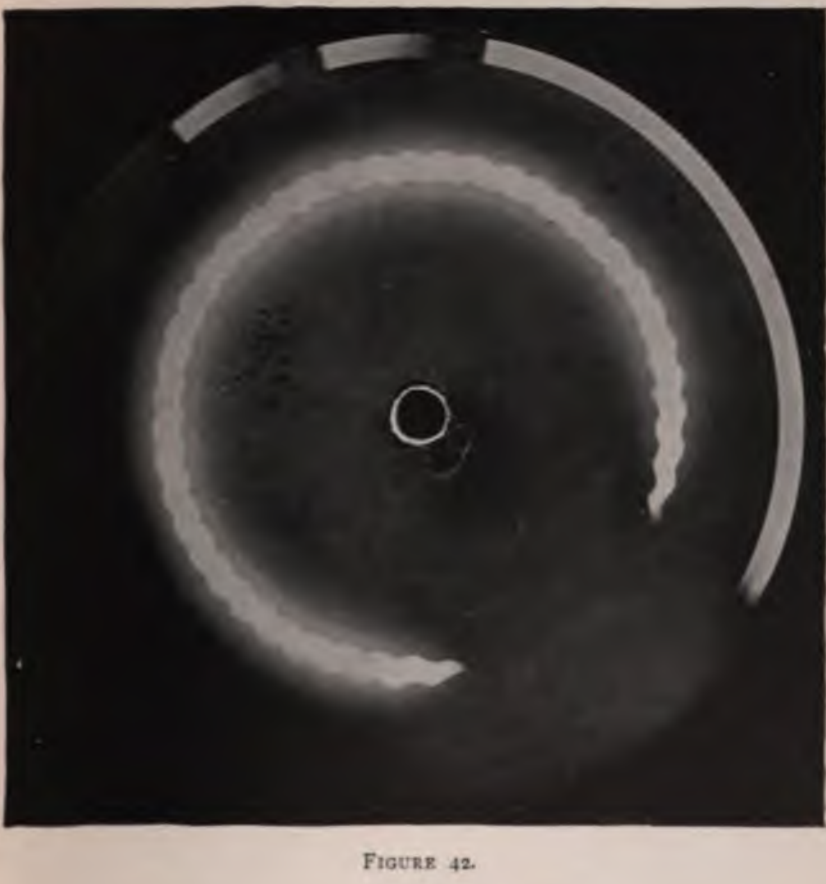


FIGURE 42.

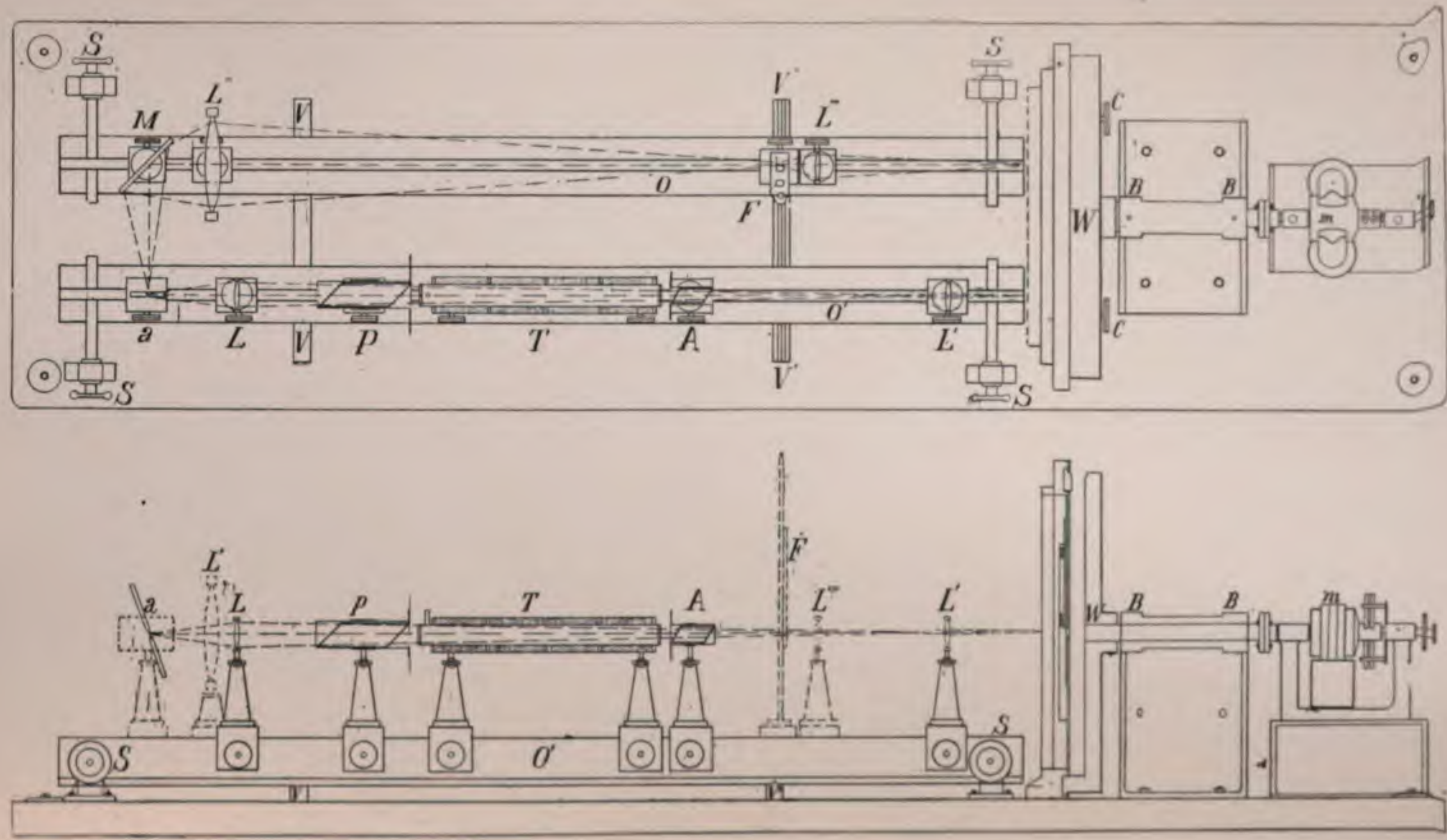
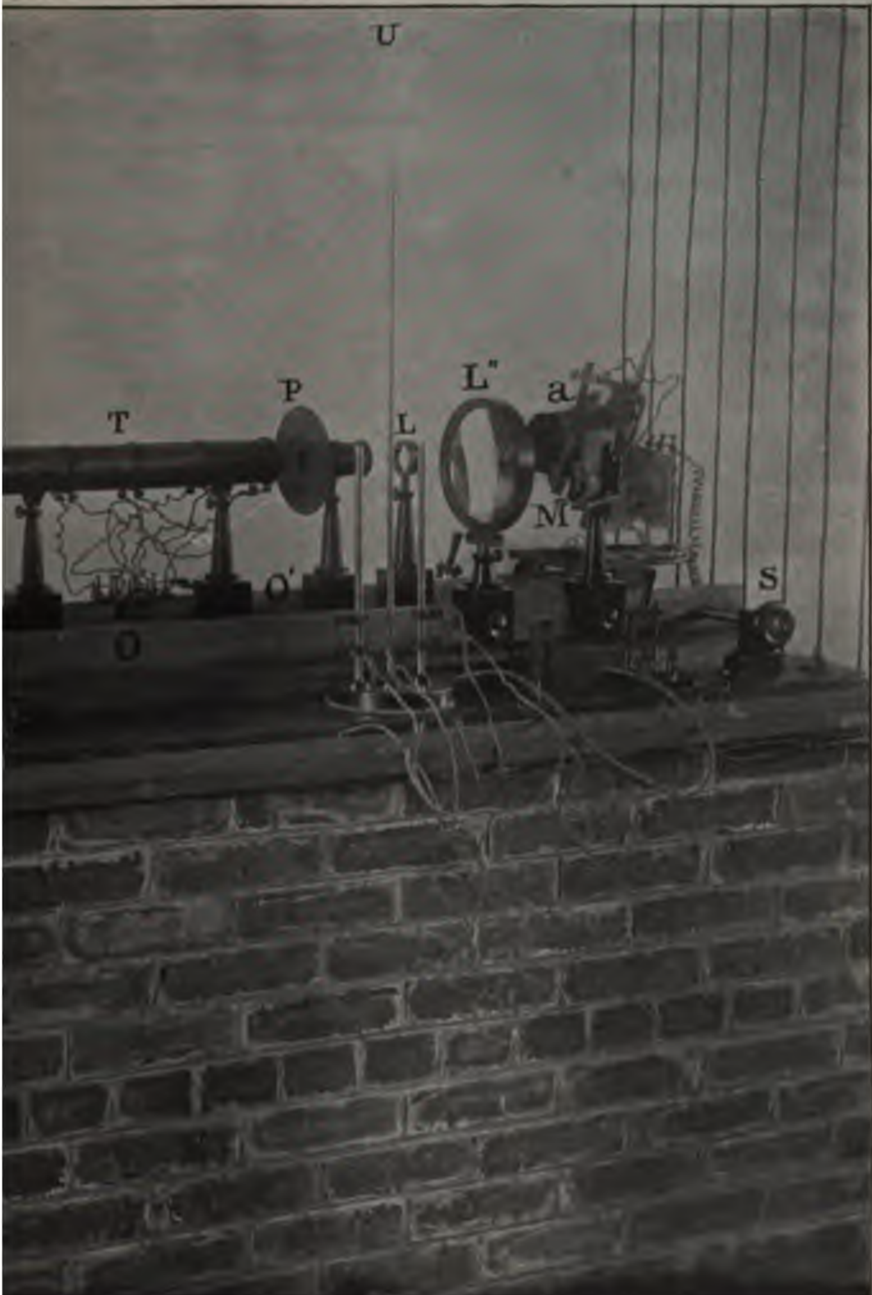


FIGURE 43.



-CHRONOGRAPH,
VA.

THE POLARIZII

FO

-CHRONOGRAPH,
VA.

FIGURE 46.—Details of Shaft and Bearings for Camera Wheel.

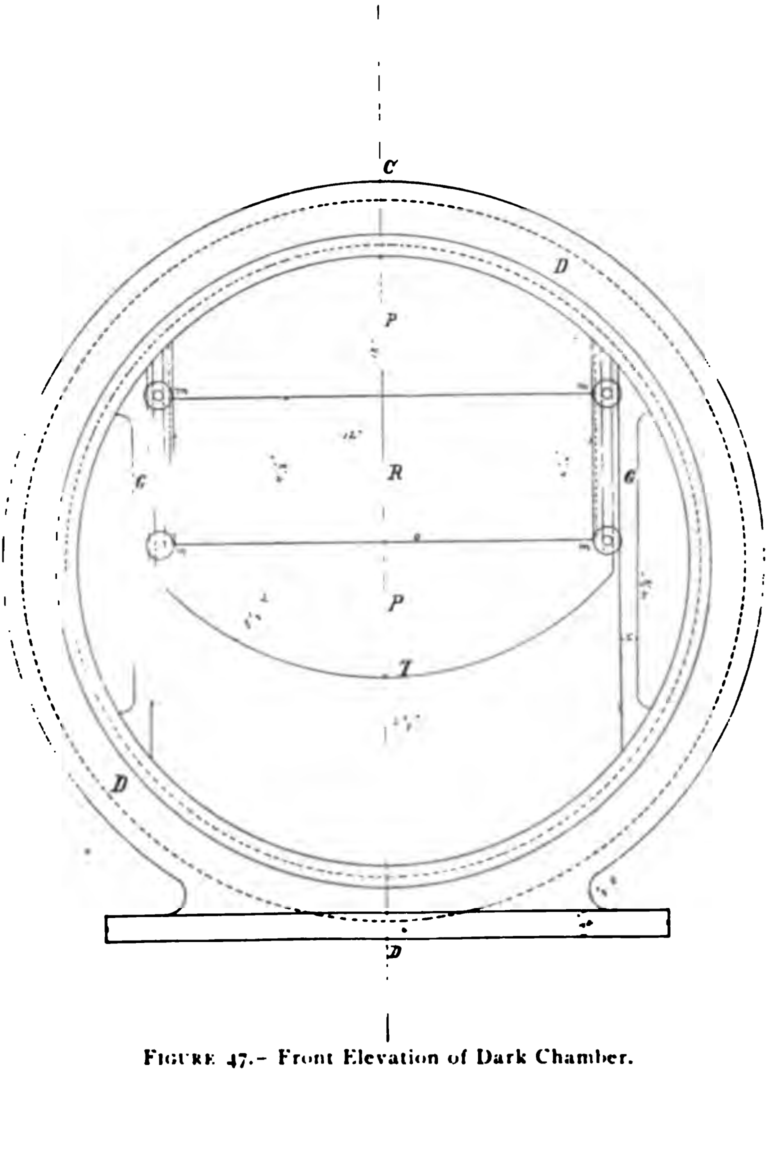


FIGURE 47.- Front Elevation of Dark Chamber.

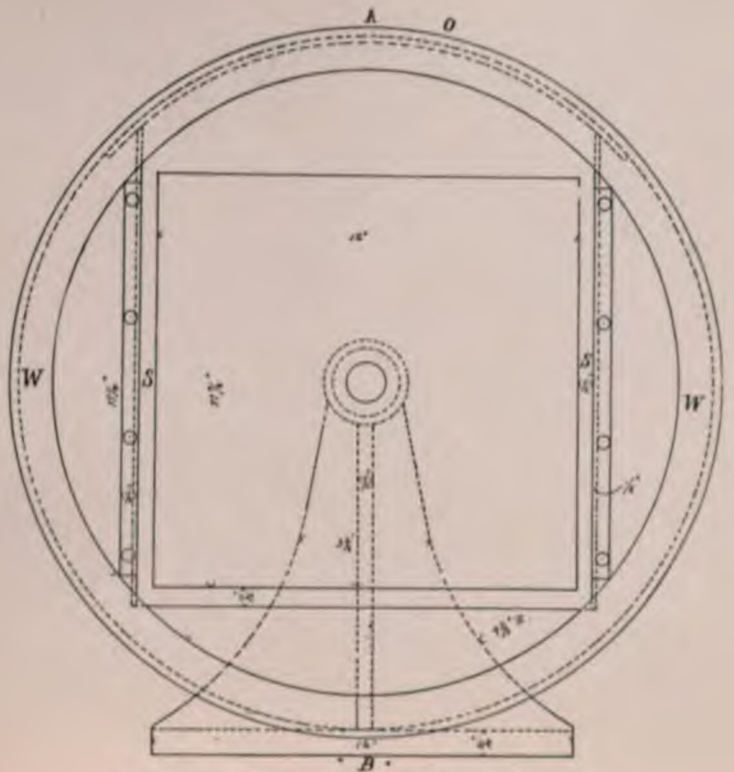


FIGURE 49.—Front Elevation of Camera Wheel.

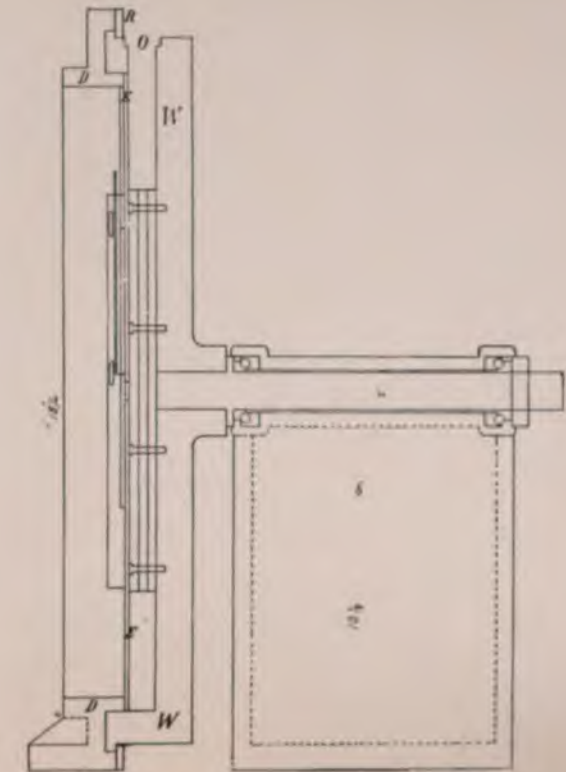


FIGURE 48.—Vertical Section through Camera Wheel and Shaft.

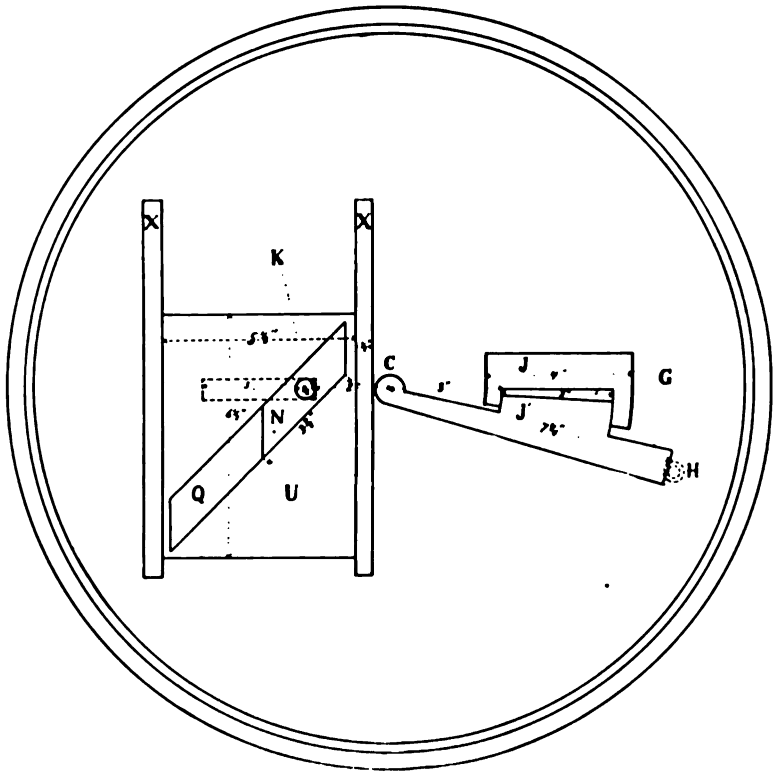
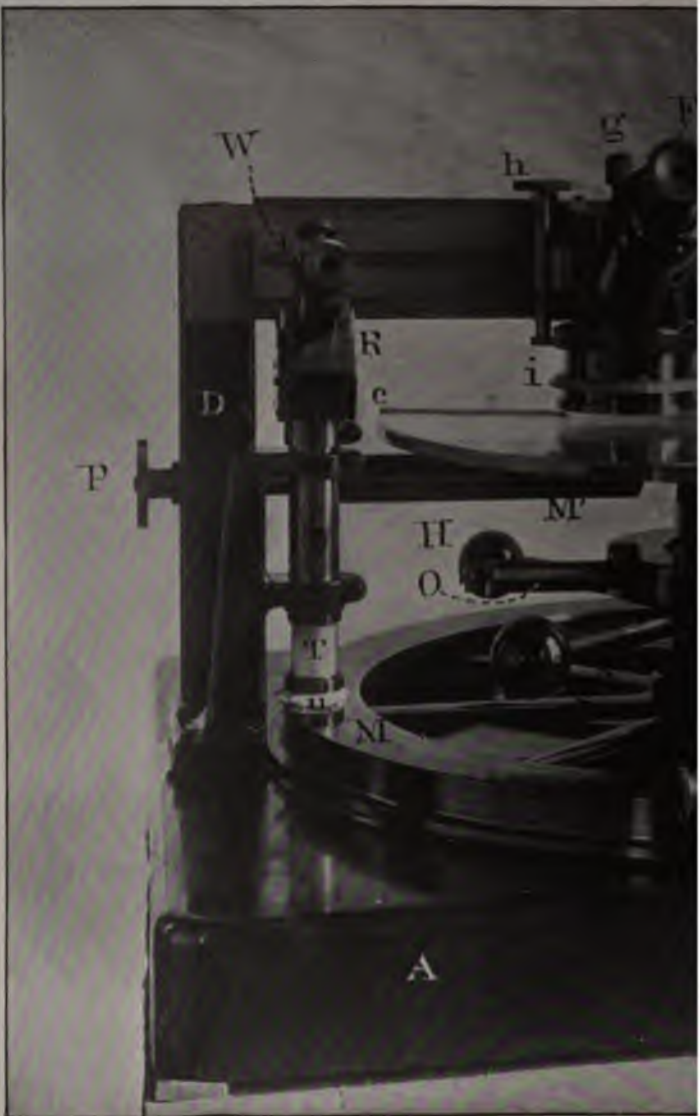


FIGURE 50. Details of Radial Slit and Fork Exposure.



THE POLARIZING PHOTO-CH

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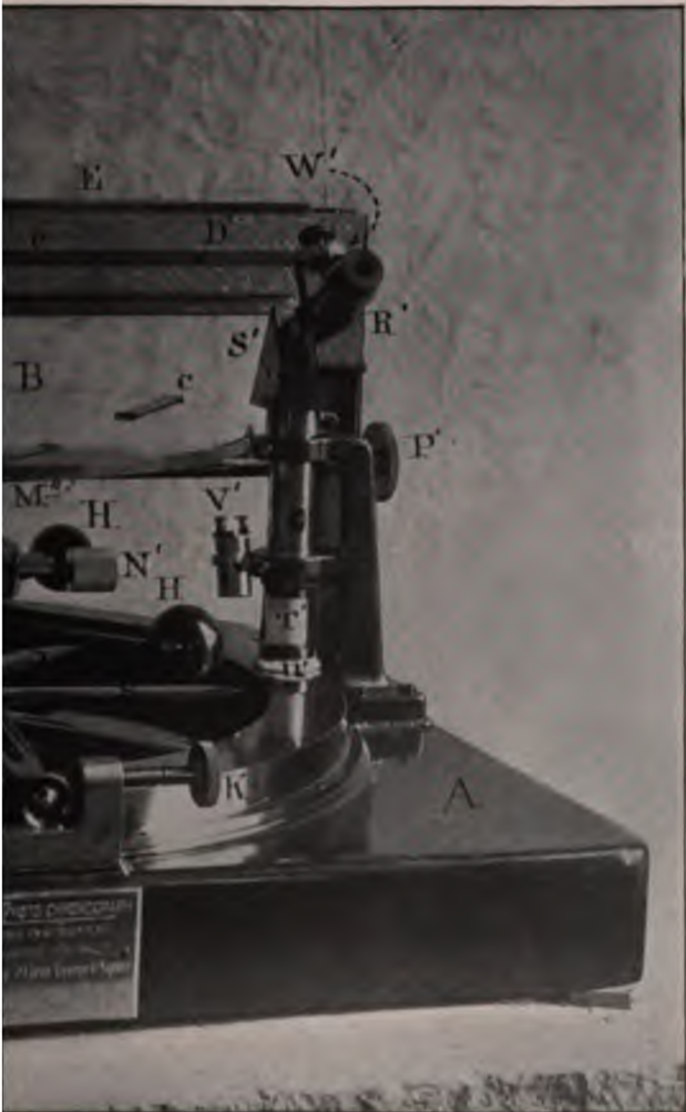


MEASURING INSTRUMENT,
A.

FIGURE 52.

COMBINED CHRONOGRAPH AND FORK RECORDS.

Tuning Fork 250 (single) vibrations per second.

Actual size of plate $12'' \times 12''$

FIGURE 53.

PART OF ACTUAL VELOCITY RECORD, 3″.2 FIELD RIFLE BY "COMBINATION" METHOD.

Tuning Fork 500 (single) vibrations per second.

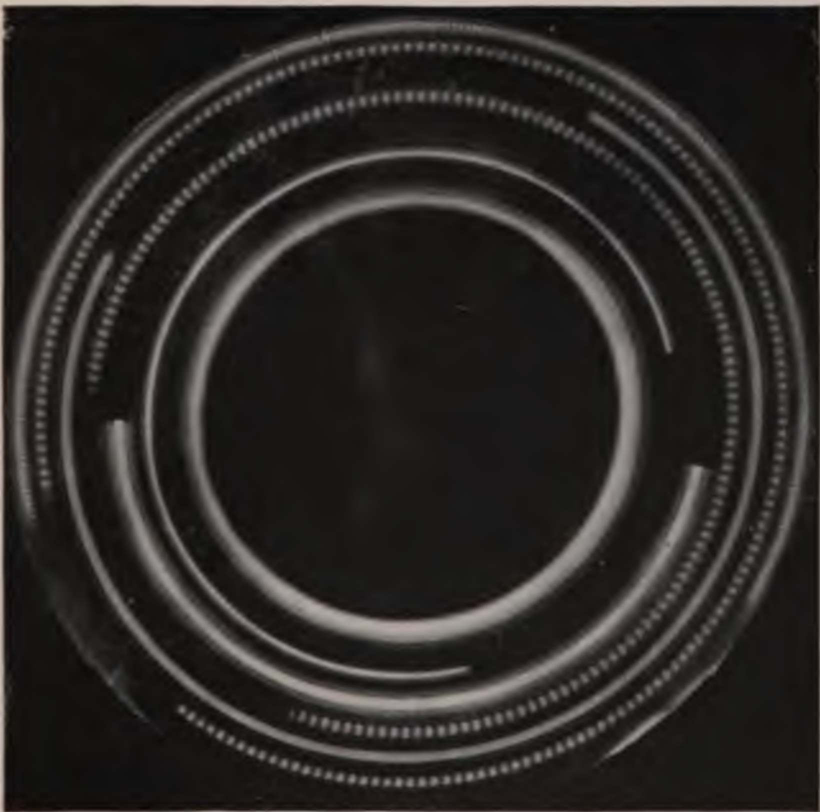


FIGURE 54.

CHRONOGRAPH RECORDS OF THE ALTERNATING CURRENT UNDER VARYING CONDITIONS OF CIRCUIT AND SPEED OF PLATE.

Actual size 12″×12″

FIGURES 55, 56, 57, 58, 59, 60.

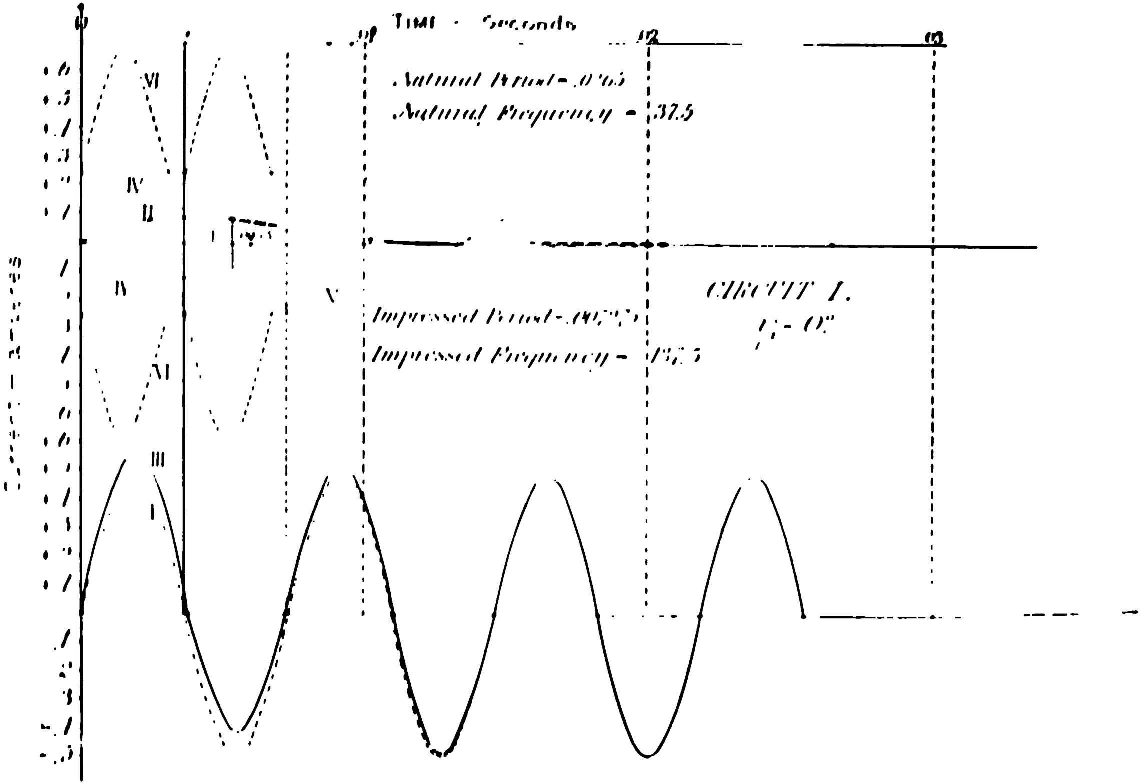
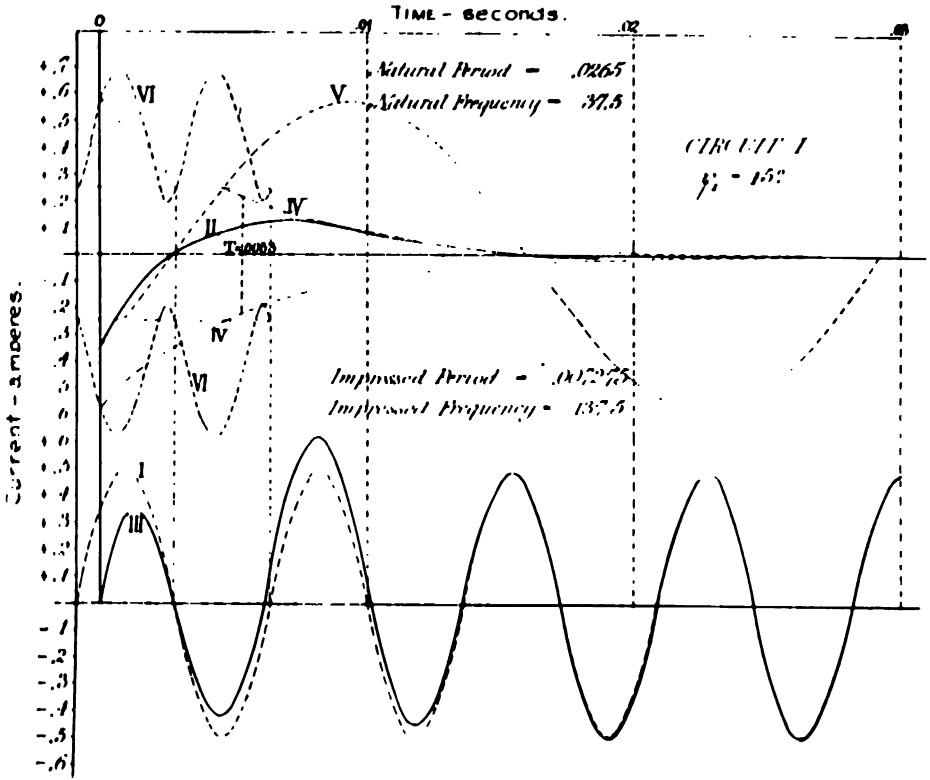


Figure 61.

Curve III. shows the Current which flows after the Introduction of an Harmonic E. M. F. into a circuit with R, L, and C. It is the Sum of the two Component Curves, I. a Sine-curve, and II. a Sine-curve with an Amplitude decreasing according to a Logarithmic Decrement.



Time - seconds.
0
.01
.02
Natural Period = .0265
Natural Frequency = 37.5
Circuit I
Impressed Period = .00727
Impressed Frequency = 137.5
Current - amperes.
I
II
III
IV
V
VI

FIGURE 62.

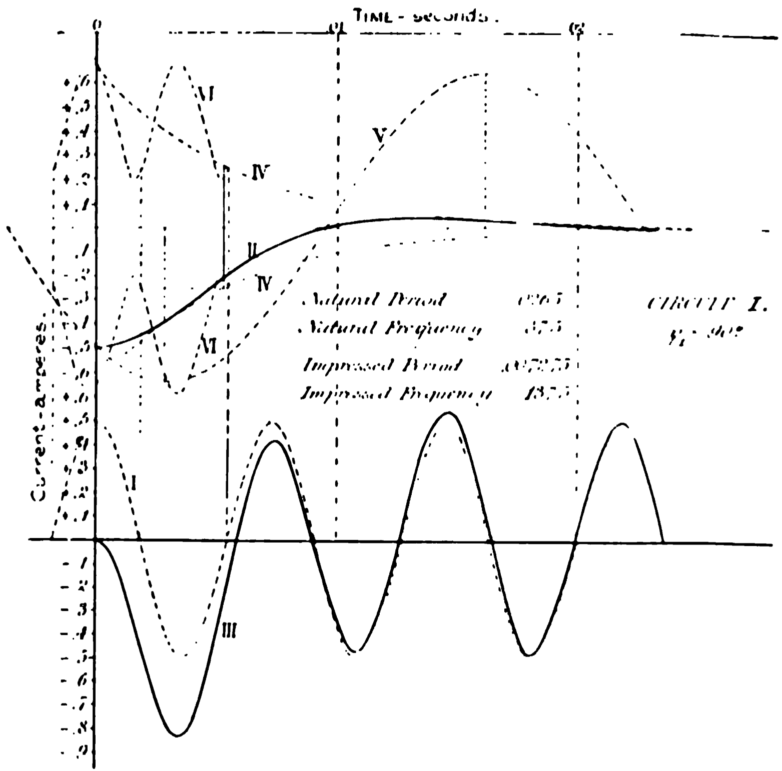
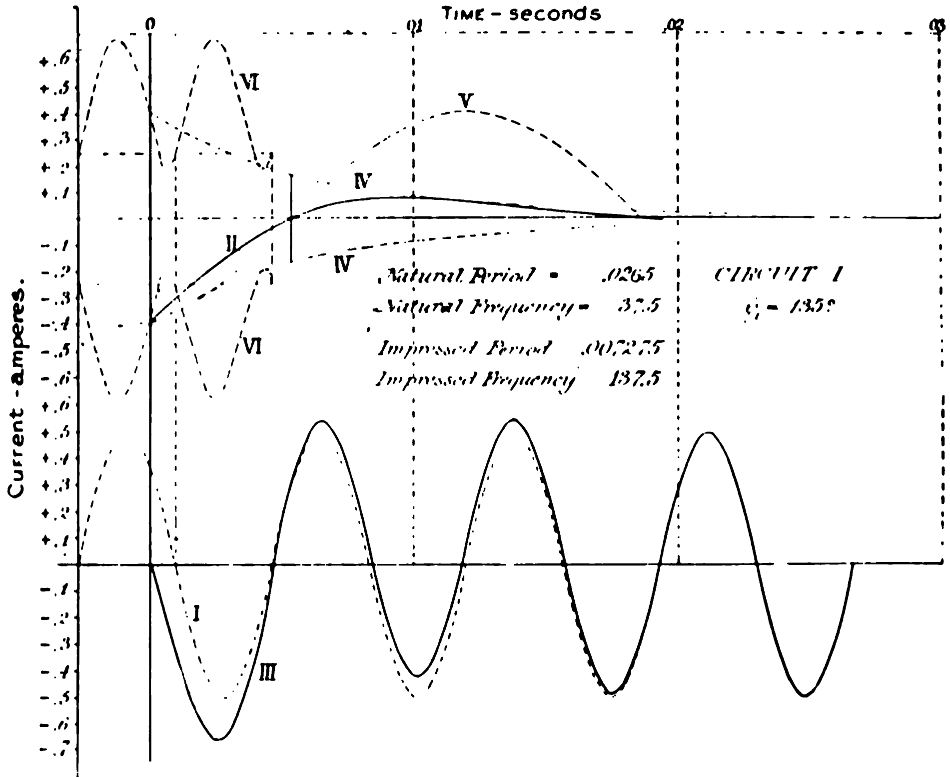
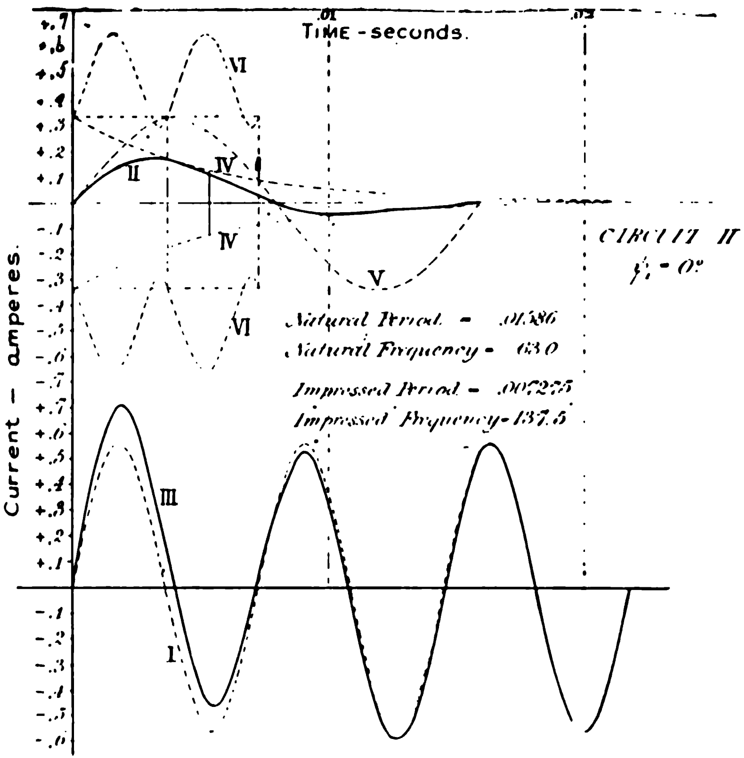

TIME - seconds.
Current-amperes.
Natural Period
Natural Frequency
Impressed Period
Impressed Frequency
CIRCUIT I.

FIGURE 63.



TIME - seconds
0
.01
.02
.03
Current - amperes.
+.6
+.5
+.4
+.3
+.2
+.1
-.1
-.2
-.3
-.4
-.5
-.6
-.7
I
II
III
IV
V
VI
Natural Period = .0265
Natural Frequency = 37.5
Impressed Period .007275
Impressed Frequency 137.5
CIRCUIT I

FIGURE 64.



TIME - seconds.
.01
.02
Current - amperes.
CIRCUIT II
$\psi_1 = 0°$
Natural Period = .01586
Natural Frequency = 63.0
Impressed Period = .007275
Impressed Frequency = 137.5
I
II
III
IV
V
VI

FIGURE 65.

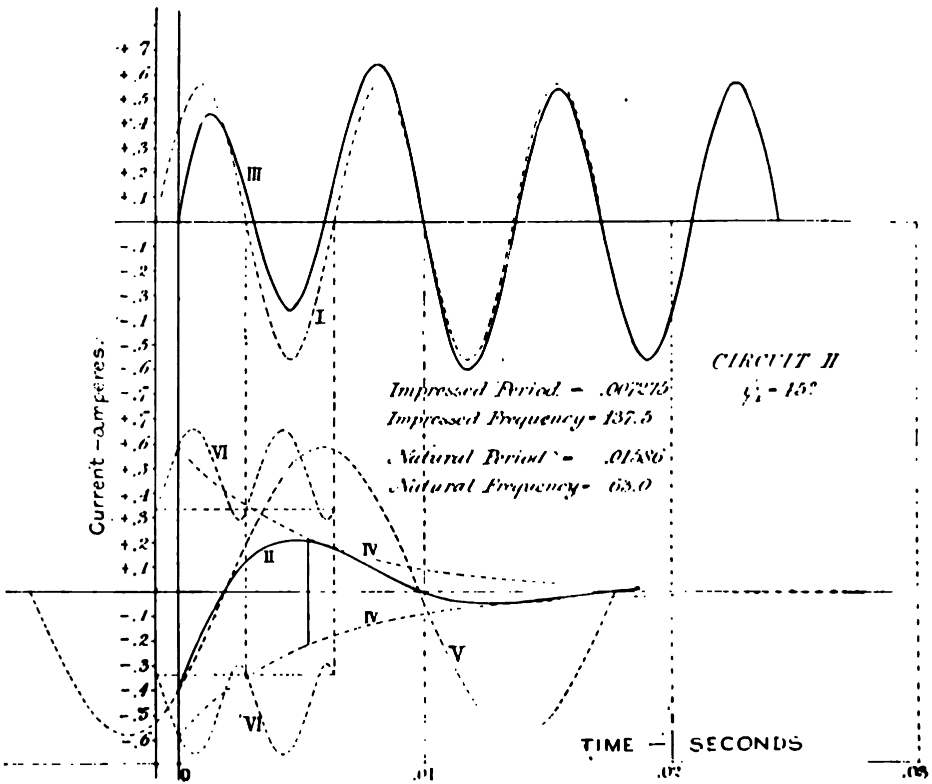

Current - amperes.
CIRCUIT II
Impressed Period = .00725
Impressed Frequency = 137.5
Natural Period = .01586
Natural Frequency = 63.0
TIME — SECONDS
I
II
III
IV
V
VI
0
.01
.02
.03

FIGURE 66.

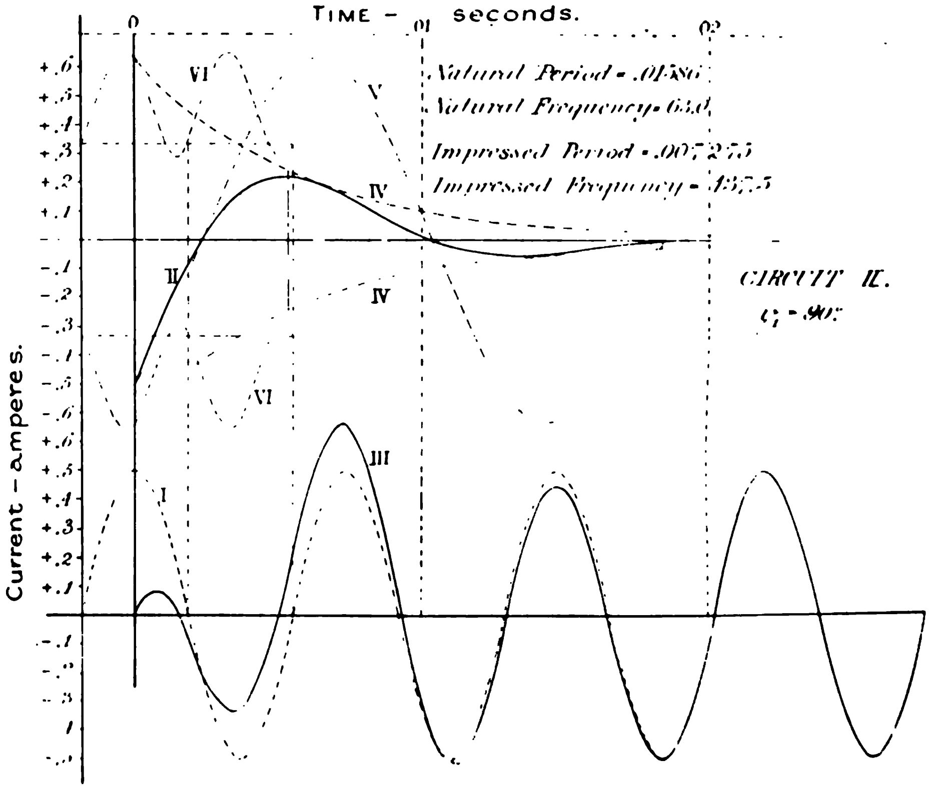

TIME - seconds.
Current - amperes.
Natural Period = .01586
Natural Frequency = 63.0
Impressed Period = .007275
Impressed Frequency = 137.5
CIRCUIT II.

FIGURE 67.

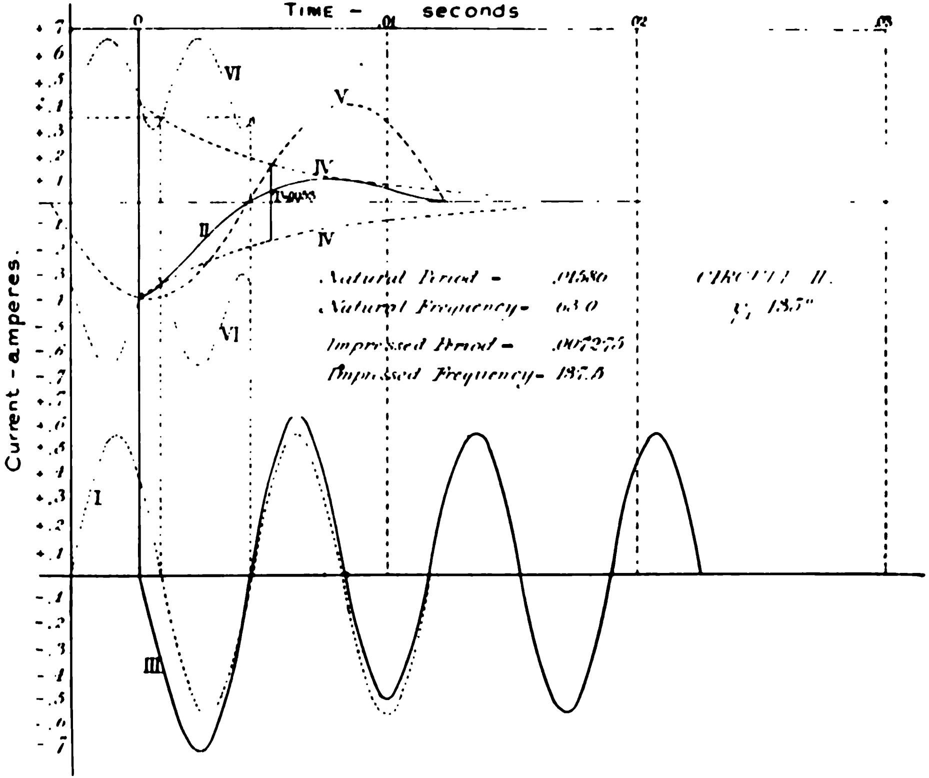

Current - amperes.
TIME - seconds
Natural Period = .01580
Natural Frequency = 63.0
Impressed Period = .007275
Impressed Frequency = 137.5
CIRCUIT II.
I
II
III
IV
V
VI

FIGURE 68.

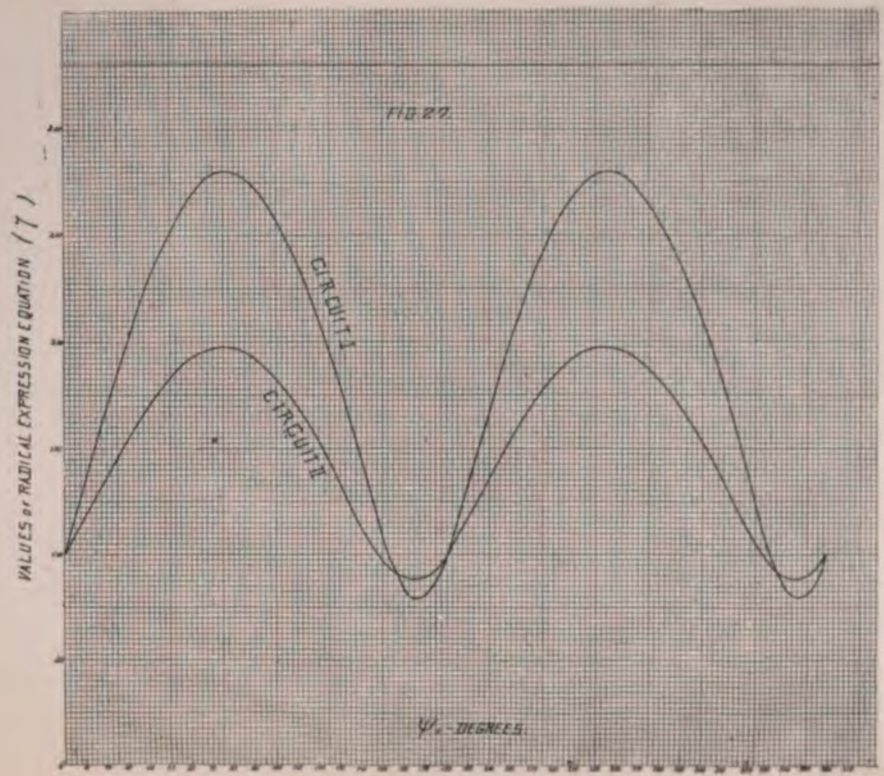


FIG. 27.
VALUES OF RADICAL EXPRESSION EQUATION (7)
CIRCUIT I
CIRCUIT II
DEGREES

FIGURE 69.

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